

An Environmental and Cost Analysis of Stamping Sheet Metal Parts

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Little work has been done on quantifying the environmental impacts and costs of sheet metal stamping. In this work, we present models that can be used to predict the energy requirements, global warming potential, human health impacts, and costs of making drawn parts using zinc (kirkcote) die-sets and hydraulic or mechanical presses. The methodology presented can also be used to produce models of stamping using other die materials, such as iron, for which casting data already exists. An unprecedented study on the environmental impacts and costs of zinc die-set production was conducted at a leading Michigan die-maker. This analysis was used in conjunction with electrical energy measurements on forming presses to complete cradle-to-gate impact and cost analyses on producing small batch size hood and tailgate parts. These case studies were used to inform a generalized model that allows engineers to predict the impacts and costs of forming based on as little information as the final part material, surface area, thickness, and batch size (number of units produced). The case studies show that the press electricity is an insignificant contributor to the overall impacts and costs. The generalized models highlight that while costs for small batch production are dominated by the die-set, the environmental impacts are often dominated by the sheet metal. These findings explain the motivation behind the research into die-less forming processes such as incremental sheet forming, and emphasize the need to minimize the sheet metal scrap generation in order to reduce environmental impacts. [DOI: 10.1115/1.4034670]

Introduction

Sheet metal stamping is used to form three-dimensional parts from flat sheet metal shapes known as “blanks.” It is widely used in the car industry to form inner and outer body panels (hoods, doors, fenders, etc.) and is used to make appliance panels like oven tops and metal sinks. Stamping typically requires two or three part-specific tools: matched profile male and female dies (sometimes referred to as the punch/post and die, respectively) are pushed together to form the final shape. A blank holder (also known as a ring) is often needed to restrain the flow of the sheet metal to prevent it from wrinkling (and help minimize springback) as it is drawn into the cavity of the female die.

Stamping is expensive; Lovell et al. [1] estimated that over \$100 billion is spent annually in the U.S. alone on the design, fabrication, and assembly of stamped parts. It is also energy-intensive; the parts are often made from steel or aluminum. Production of these two metals accounts for over 10% of global anthropogenic carbon dioxide emissions [2]. The heavy dies that form the sheet are typically made by energy-intensive casting and machining, and are pressed into the sheet using mechanisms that are often poorly optimized to the forming cycle load characteristics [3].

Studies that examine the energy required to make a stamped part typically ignore the energy invested in making the sheet metal, lubricant, and die-set. The claims made in the literature are often unreliable because they are based on simulations of the stamping process rather than on data gathered from case studies. This is because researchers are often focused on evaluating an emerging technology and make claims regarding stamping only when referring to the emerging technology’s potential to supersede it. Examples include Peltier and Johansson [4] and Matwick [5] with regards to hydroforming; Luckey et al. [6] with

regards to superplastic forming; and multiple authors with regards to die-less incremental sheet forming [7–11]. The emerging sheet metal forming technologies are typically used to form small batches of parts in the hundreds rather than the tens of thousands of units. Analogous stamping typically uses zinc dies that are easy to cast but wear quickly. No cost or environmental impact study on zinc die production has been found in the literature.

Several researchers report the electrical energy needed to operate a stamping press. Some express the energy needed per stroke of the forming press [3,12]; whereas, others state the energy needed per kilogram of sheet metal formed [13–17]. It is unclear which of these normalizations is the most helpful when predicting the energy required to form a part.

No holistic analysis on sheet metal forming costs has been found in the literature. Several authors, such as Tang et al. [18], constructed relationships between final part geometrical features and tooling costs. In a similar vein, Ficko et al. [19] identified the cost-defining geometric features of previously produced stampings and then estimated the cost of new stampings based on their empirical findings. For the production of small batch sizes, Poli [20] stated that, due to short forming times, and therefore, low energy and labor costs, the die and sheet metal account for the majority of costs. It can also take up to 10 weeks to manufacture a matched die-set [12], adding significant lead time to any project.

In light of these findings, this study addresses the following questions:

- (1) What are the environmental impacts of making zinc stamping dies?
- (2) How much energy is needed to operate a forming press?
- (3) What are the overall environmental impacts and costs of making sheet metal parts?

This study focuses on the impacts and costs of the main stamping station; some complex parts require incremental forming over multiple die-set stations. This study considers stamping with zinc die-sets in order to provide an appropriate benchmark for the researchers evaluating emerging forming technologies generally used for small batch sizes. No previous study on zinc die

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Contributed by the Manufacturing Engineering Division of ASME for publication in the JOURNAL OF MANUFACTURING SCIENCE AND ENGINEERING. Manuscript received August 17, 2016; final manuscript received September 1, 2016; published online November 2, 2016. Editor: Y. Lawrence Yao.

production has been found in the literature, whereas environmental data already exist for the casting of other key metals; for example, Rossie [21] described the environmental impacts of casting iron, and Dalquist and Gutowski [22] performed a life cycle analysis of a generic metal casting process. The results of this study could be used to expand and refine the life cycle inventory (LCI) database values for stamping and die making. As highlighted later in this paper, LCI database entries often lack processing details, and modeling choices are often poorly documented.

The environmental analyses conducted in this study are “cradle-to-gate” life cycle assessments: the analysis starts from resource extraction and ends at the output of the forming process. The “recycled content” approach is used, which reflects a strong sustainability concept where the impacts are accounted for when they occur and the producer of scrap receives no credit. The impacts considered are the cumulative energy demand (CED), also known as primary or embodied energy, cumulative carbon dioxide equivalents emitted, also known as embodied carbon dioxide, which is a measure of global warming potential (GWP) with a 100-year time horizon, and human health impacts in disability-adjusted life years (DALYs). The impacts are modeled in SimaPro software [23] using the ecoinvent 3.1 database [17] and CED version 1.09 and IMPACT2002+ version 2.12 impact assessment methodologies. Primary data have been collected in the case studies. In order to reduce confusion, in this paper “MJ” is used when referring to the CED, “kWh” when referring to metered electricity use, and “therm” when referring to the energy content of natural gas.

The Impacts of Making Zinc Stamping Dies

Making a zinc die requires the melting of a zinc alloy (typically kirkcote) at 430 °C, and sand casting of the die shape with up to 10 mm of excess material on all sides. This excess is then machined away using computer numeric control (CNC) milling machines. Finally, hand-grinding operations during die-set assembly and die try-out (cycling the press and making practice parts) ensure smooth contours on the sheet-contacting surfaces and correct fit between the die-set pieces.

The environmental impacts are modeled by examining the foundry and machining shop operations at leading car die-makers situated in south-east Michigan. The following data are required: (1) zinc recycled content; (2) the fuels, electricity, and materials used in zinc casting; (3) the fuels, electricity, and materials used in machining the cast zinc to the final die shape. Interviews with the car industry revealed that the recorded mass of a zinc die refers to its post casting (including gate and dross removal) but premachined state. In light of this, the modeling results in this section present the impacts of making the cast premachined die and the impacts of machining that die separately. The impacts are normalized per kilogram of cast premachined die and per kilogram of zinc removed by machining.

Recycled Content. Visiting and interviewing three leading zinc foundries in southeast Michigan determined the recycled content. The visits led to a consistent narrative being constructed of zinc material mass flow, presented in Fig. 1. Two of the interviewed foundries are die-makers (whose activities include “die casting” and “machining” in Fig. 1), and the third foundry (“external foundry” in Fig. 1) supplies the die-makers with zinc ingots. The material flow presented in Fig. 1 has been corroborated by one of the die makers. The companies provided information on the condition of anonymity.

In the die casting step, molten zinc is poured from a natural gas fired furnace into a sand mold. Once cooled, the gates (channels in the sand used to fill the shape with metal) are removed. Subsequently, the die is CNC machined to achieve its final shape. The gates, machining chips, and dies themselves can all be recycled to make more dies. The gates will be recycled in-house shortly after the die is manufactured. After being used (typically by car

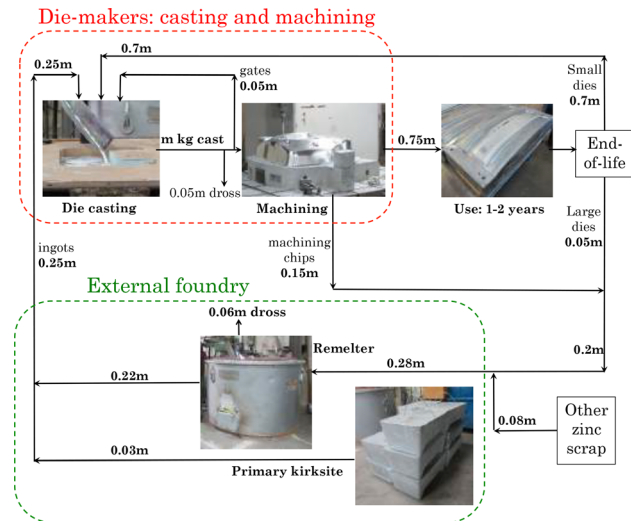


Fig. 1 Zinc mass material flow. Mass of zinc (m kg) cast.

companies for 1–2 years), the die-sets are returned to the die-makers. The smaller die-sets are recycled by the die-makers; however, typically their furnaces are too small for the larger dies (for example, those used to make car side body panels). Additionally, they cannot recycle machining chips because they have inadequate equipment to handle the high oxide content, lubricant, and tendency of the chips to spit back out of the melt. As a result, the die-makers send both large end-of-life dies and machining chips to the larger external foundry.

Remelting of gates and small end-of-life dies accounts for 75% of a die-maker’s casting input. The remaining 25% is from the external foundry, of which a tenth is primary zinc (made from ore). This primary zinc allows adjustments to ensure an acceptable alloy mix. The automotive industry provides most of the zinc the external foundry recycles.

In total, the recycled content of a new die is 97.5%. This figure is much higher than the worldwide zinc recycled content of 21–25% [24], but this investigation has found that zinc casting alloys are often supplied through stable, regional material loops established to supply stable demand, in this case prototype die-sets for the car industry. As part of a sensitivity analysis, we use a recycled content of 90% in addition to 97.5%. The inputs modeled are shown in the Appendix: *Purchased zinc from external foundry*. Ecoinvent 3.1 has a database entry for primary zinc that is used to model the primary material needed in this analysis. Additionally, furnace energy consumption at the external foundry was not measured and must be estimated. Ashby [24] reported the CEDs of recycled zinc alloys as 10–12 MJ/kg. The lower end of this range (10 MJ/kg) is taken as representative in this study as kirkcote is only lightly alloyed with aluminum. Thus, the remelter is modeled using an ecoinvent 3.1 furnace entry with natural gas requirements equivalent to 10 MJ CED per kilogram of zinc poured. The premachined die corresponds to 90% of the cast metal (10% material loss from dross and gates removal) so the inputs per kilogram of zinc poured are divided by 0.9.

Zinc Sand Casting. One of the Michigan die-makers provided foundry gas consumption data and the mass of zinc poured for each month from January 2008 to January 2014. Figure 2 shows this data aggregated into annual values.

Between 2008 and 2013, the average gas consumption at the die-maker’s foundry was 0.05 therms_{gas}/kg_{zinc poured}. Figure 2 shows that the annual gas consumption was not closely related to the mass of zinc poured, implying a high standby (base load) power requirement that was independent of production. This result may correspond to the burning of gas to keep the furnace hot

during idle periods. As part of a sensitivity analysis, the highest annual efficiency recorded for the gas furnace ($0.03 \text{ therm}_{\text{gas}}/\text{kg}_{\text{zinc_poured}}$) and lowest efficiency ($0.13 \text{ therm}_{\text{gas}}/\text{kg}_{\text{zinc_poured}}$) were also modeled. The foundry casting operations were modeled using an ecoinvent 3.1 furnace database entry (see the Appendix: *Zinc sand casting*).

The molten zinc is poured into a sand mold. Making this mold starts with a pattern that is cut and machined from expanded polystyrene. Sand containing a small amount of bentonite clay and mixed with water is compacted around this pattern. No cores are used in zinc stamping die casting. After the die is made, the sand is reused for up to 3 years. In light of this, when modeling the impacts of mold making, the use of sand and bentonite has been neglected. The sand consumption rate is, however, needed to estimate the water demand. The sand consumption was estimated from Dalquist and Gutowski [22] at $5.5 \text{ kg}_{\text{sand}}/\text{kg}_{\text{zinc_cast}}$, and the amount of water (as a fraction of the sand mass, 0.034) was provided by the die-maker. The mass of polystyrene required to make a pattern was estimated using the densities of zinc ($6920 \text{ kg}/\text{m}^3$) and polystyrene ($16 \text{ kg}/\text{m}^3$), and by assuming that 25% of the polystyrene purchased by the die-maker is wasted during the pattern-making (machining) process. The electricity used in mold making was estimated from a Department of Energy report indicating that, while metal melting accounts for 55% of a foundry's direct energy use, mold making accounts for as little as 7% [25]. The impacts of mold making are modeled in SimaPro as summarized in the Appendix: *Mold Making*.

Zinc Machining. The cast die is machined to the final shape. First, the bottom of the die is leveled in a step called "basing," where 10 mm of material is removed. Second, "roughing" operations on the sides and top also remove approximately 10 mm of the material. Finally, the top (sheet contacting) surface of the die is machined with a very fine step size, removing a further 1.5 mm of zinc. Collectively, these machining operations remove about 15% of the cast mass.

In order to calculate the impacts of machining, a case study was conducted at one of the Michigan die-makers: the electrical power used in CNC milling machines during roughing and finishing of a zinc post (part of a die-set used to make car rear window supports) was recorded using a Fluke 434 (Series ii) three-phase power analyzer. The results are shown in Fig. 3.

Despite the lower power draw, finish milling requires much more energy per unit mass because it takes much longer to remove a unit of material. Machining zinc also requires the use of cutting fluid (lubricant and water) and compressed air. These were not directly measured at the die-maker but are modeled using ecoinvent 3.1. Ecoinvent uses the same amount of consumables per kilogram of metal machined across its iron, steel, and aluminum entries.

Impact Results for Making a Zinc Die. The environmental impacts of zinc die production are summarized in Table 1.

The impacts of making the premachined die are dependent on the zinc-recycled content and the melting furnace efficiency. Figure 4 shows the effect of variations in furnace efficiency (equivalent to the maximum and minimum furnace efficiency at the die-maker between 2008 and 2013), and a hypothetical scenario in which the recycled content of the zinc is reduced to 90%.

The Energy Needed to Operate a Forming Press

Electrical power measurements were taken on hydraulic and mechanical stamping presses at a Michigan die-maker using a Fluke 434 (Series ii) three-phase power analyzer. Despite being slower than mechanical presses, hydraulic presses are often used during prototyping or low volume production as the load and ram velocity can be decoupled, aiding control of the forming process. In mechanical presses, the drive system transfers power from a

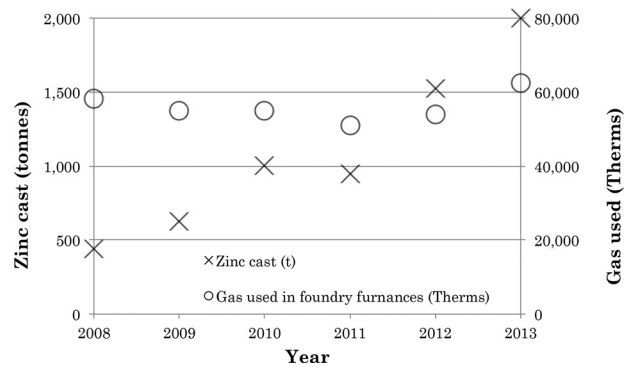


Fig. 2 Collated annual data from the zinc die-making foundry

motor via connecting rods to the drawing slide with load peaks compensated using a flywheel. As discussed in the introduction, previous studies have expressed the energy required to operate a stamping press either per kilogram of formed sheet or per stroke (cycle) of the press. In order to examine which is the most appropriate normalization, in this study, forming of different size parts is simulated by changing the forming load and measuring the difference in the electrical energy required to cycle the press.

Hydraulic Press. The hydraulic press used in this analysis was manufactured by "Lake Erie Engineering Corporation" and can apply a maximum load of 800 short ton. The press rams are powered by 75 HP and 60 HP induction motors both operating at 1200 rpm. The press was used to make a series of prototype 1 mm thick aluminum truck hoods, each weighing 5.4 kg. The forming load required was 750 ton.

Prototyping involves short production runs, often with intermittent breaks to ensure the quality of the formed parts. Figure 5 presents one such run for forming seven hood parts. The average cycle time is 170 s (2.8 min) with average energy requirements of 1.2 kWh/part.

Power measurements were taken during forming of an eighth part, during which the power factor and the position of the top (female) die are also recorded. These measurements are shown in Fig. 6.

Figure 5 shows a power spike at over 200 kW corresponding to the current surge when the press is turned on. Standby power requirements are then 19 kW. As the top die descends, the power required grows to 32 kW. Contact between the female die and ring (blank holder) prompts a rapid increase in power requirements. As the draw cushion is compressed the power requirements continue to grow. The die descends approximately 150 mm while forming the sheet over the post. Contact between the die and rigid post results in a power spike at just over 120 kW. The power

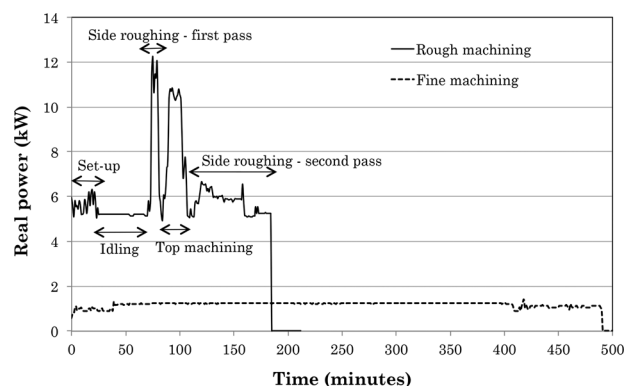


Fig. 3 Zinc machining power measurements (roughing: 19 kWh to remove 42.5 kg; finishing: 9.6 kWh to remove 2.5 kg)

Table 1 The environmental impacts of zinc die-making

	Cumulative energy demand (CED)	Global warming potential (GWP)	Human health impacts
Units	MJ/kg _{cast}	kgs.CO _{2eq} /kg _{cast}	DALYs/kg _{cast}
Zinc die (premachined)	16.4	1.0	9.7×10^{-7}
Units	MJ/kg _{removed}	kgs.CO _{2eq} /kg _{removed}	DALYs/kg _{rem.}
Zinc milling (roughing and basing)	9	0.46	2.9×10^{-7}
Zinc milling (finishing)	54	3.08	2.0×10^{-6}
Zinc milling (average)	10	0.56	3.5×10^{-7}

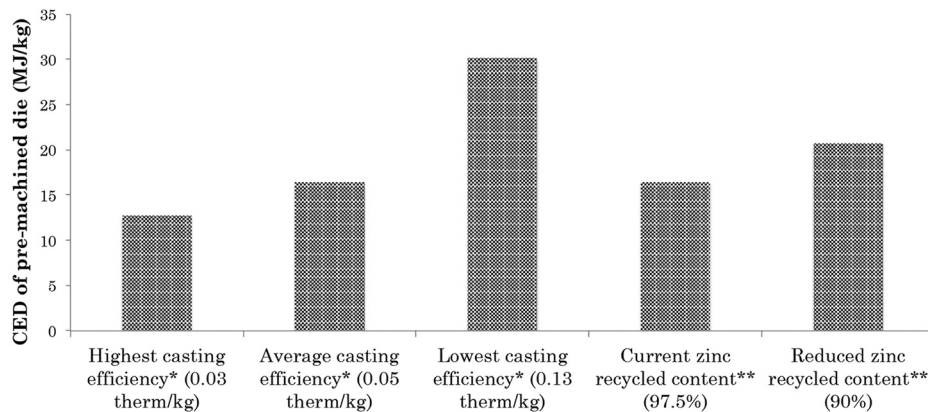
factor is only 0.5 during most of the forming process. This means high currents from reactive power flow and therefore line and transformer energy losses. The power factor spikes at 0.9 as the die contacts the post and applies the full forming load.

In order to simulate forming a smaller part, the forming load was reduced from 750 ton to 500 ton, and the measurements repeated. The only effect was to limit the height of the power peak during forming to 100 kW (from 120 kW, see Fig. 6), making a negligible difference to cumulative energy. In light of this result, for a hydraulic forming press electrical energy requirements per stroke are an appropriate normalization. In comparison to previous researchers, the hydraulic press energy requirements found in this study (1.2 kWh/part) lie between those reported by Schuler (0.22 kWh/part) [12] and Zhao et al. (1.46 kWh/part) [3]. Schuler's measurements may be lower because they were taken

on presses used on a mass production line with a continual throughput of parts, reducing the significance of standby power requirements.

Mechanical Press. The mechanical press used in this analysis was a Clearing mechanical double action press that can apply a maximum load of 850 short ton. The press is driven using a fly-wheel powered by a 100 HP motor. A 3 HP motor powers pumps for lubrication and cooling. Air cylinders inside the unit are used to either release the brake (causing the press to cycle) or to stop the flywheel. The compressed air is supplied from a central facility within the factory. It is assumed that the impacts of the compressed air used in this one press are negligible.

The press is not directly force controlled but rather the 100 HP motor speeds up the flywheel. The brake can be released at any



*With a zinc recycled content of 97.5%

**With a casting efficiency of 0.05 therm /kg

Fig. 4 Zinc die-making sensitivity analysis

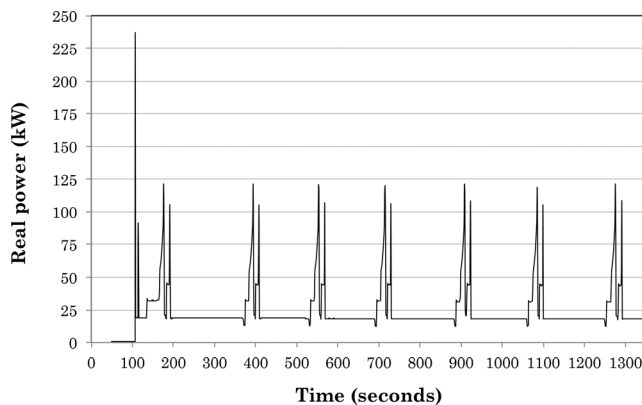


Fig. 5 Power profile during forming of seven-parts on the hydraulic press (750 ton loading)

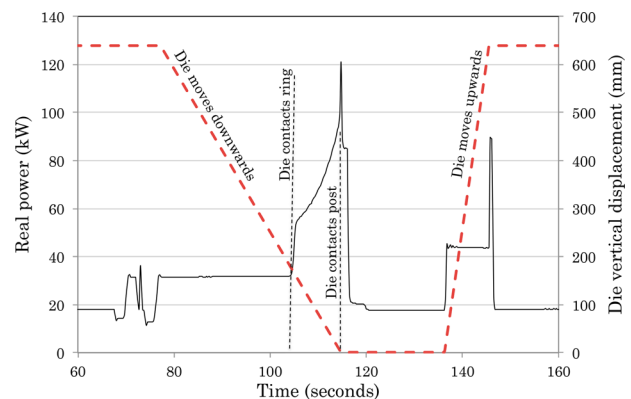


Fig. 6 Power profile and die displacement for hydraulic press

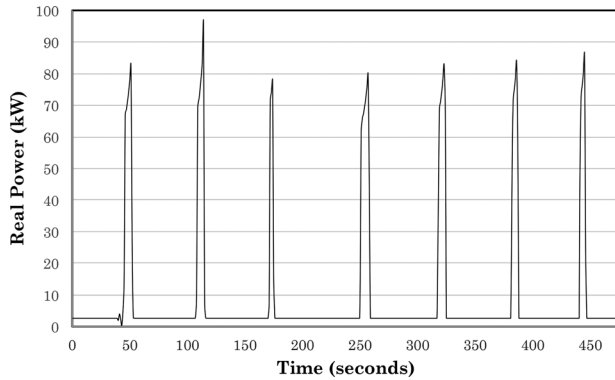


Fig. 7 Power profile for forming of seven parts on the mechanical press

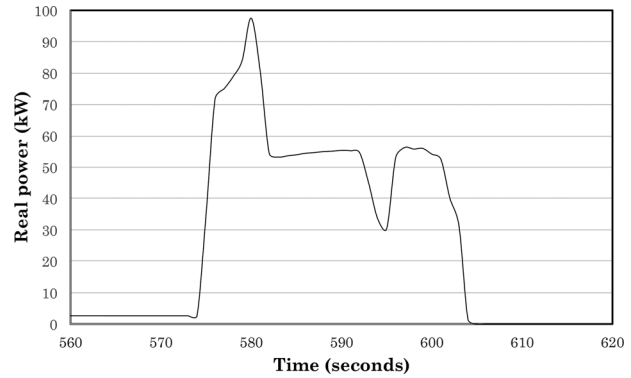


Fig. 9 Power profile for forming a part using a mechanical press. Loading of approximately 850 short ton.

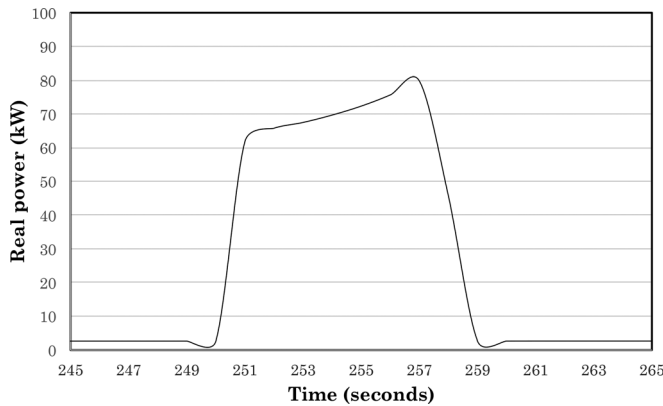


Fig. 8 Forming of one part using mechanical press

time during this speed up and the press will cycle. The flywheel must be spinning at full speed in order to apply the full 850 ton loading.

The press was used to make a series of prototype 1 mm thick aluminum truck tailgates, each weighing 3.0 kg. The parts were made using a forming load of approximately 650 ton. Achieving this load required the press operator to guess the point during the acceleration of the flywheel the brake should be released, forming a part. Figure 7 presents a run of seven parts. The variations in the

peak power are due to variations in when the operator released the brake. The average cycle time (including loading and unloading blanks/parts) is 1 min, with an average electrical energy requirement of 0.2 kWh/part. This mechanical press energy requirement is comparable to that found by Schuler (0.1 kWh/part) [12] in a mass production environment.

Figure 8 shows a close-up of the power profile for the fifth part produced. The standby power is only 3 kW and corresponds to the small motor used to pump lubricant and coolant.

In order to simulate forming a larger part, the flywheel was accelerated to maximum speed (850 ton forming load) and the press cycled. The power profile is shown in Fig. 9. Between 574 and 595 s, the motor first accelerates and then maintains the maximum speed of the flywheel. The operator then cycles the press (595–605 s).

For the case of the mechanical press, the forming load makes a big difference to the overall forming energy. The energy needed per part increased from 0.2 kWh/part for 650 ton loading to 0.5 kWh/part for 850 ton loading. In light of this, “energy per stroke” is not an appropriate normalization for a mechanical press. A larger study would be needed to determine an appropriate normalization for the mechanical press energy requirements.

The Overall Impacts and Costs of Making Sheet Metal Parts

Two case studies on 250-part production of aluminum car parts were completed in order to evaluate the overall environmental

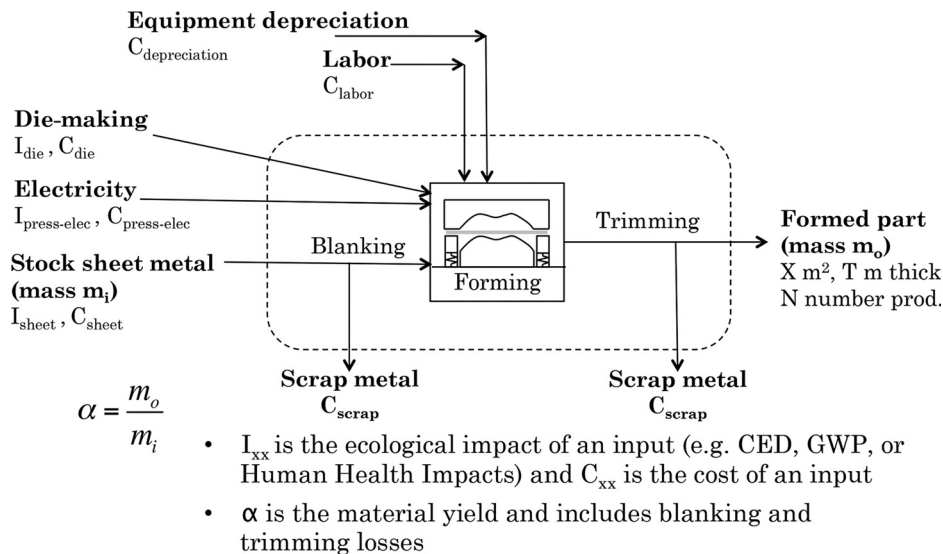


Fig. 10 The ecological impacts (I_{xx}) and costs (C_{xx}) of forming sheet metal parts

Table 2 Part and die-set data provided by a Michigan die-maker

Part made	Die-set			Part description				
	Material	Mass cast (kgs)	Die-set cost (USD)	Material	Thickness (mm)	Stock sheet area (m ²)	Blank area (m ²)	Part area (m ²)
Truck hood prototype	Zinc	13,190	47,000	Aluminum (AA6014)	0.95	3.70	3.00	2.10
Truck tailgate prototype	Zinc	6850	47,000	Aluminum (AA6014)	0.95	3.70	2.14	1.16
Car hood	Zinc	7410	53,500	Steel	N/A	N/A	2.00	1.35
Car roof	Zinc	15,630	50,000	Steel	N/A	N/A	3.10	2.48
Car front door outer	Zinc	6970	39,000	Steel	N/A	N/A	1.59	0.97
Car rear door outer	Zinc	5950	39,000	Steel	N/A	N/A	1.57	0.84
Car front fender	Zinc	6440	44,000	Aluminum	N/A	N/A	1.60	0.65
Car side body panel ^a	Zinc	22,730	N/A	N/A	N/A	N/A	4.39	1.67
Small truncated cone ^b	Steel	1132	N/A	N/A	N/A	N/A	0.14	0.09

^aMass of zinc die-set taken from alternative supplier (Imanishi Manufacturing Co.). Blank and final area of car side panel taken from Omar [26].

^bTheoretical: die size calculated using equations from Dittrich [27].

impacts and costs of making sheet metal parts. The case study analyses use the boundaries depicted in Fig. 10.

The case studies were used to evaluate the importance of the different inputs. A generalized model of impacts and costs was then constructed where predictions can be made based on as little information as the final part material (aluminum or steel), surface area, thickness, and the lifetime number of parts produced on a die-set.

Case Studies: Aluminum Hood and Tailgate. The case studies were conducted at a Michigan die-maker. The first case study produced aluminum truck hoods (part size and die-set information presented in the first row of Table 2) on an 800 ton hydraulic press (forming load of 750 ton, 1.2 kWh/stroke). The second case study produced aluminum truck tailgates (part size and die-set information presented in the second row of Table 2) on an 850 ton mechanical press (forming load of 650 ton, 0.2 kWh/stroke). Photographs of the case study parts are shown in Fig. 11.

Impacts and Costs of Inputs. The case study analyses include: (1) die making (I_{die} and C_{die}); (2) the electricity used in the

stamping press ($I_{press-elec}$ and $C_{press-elec}$); and (3) the sheet metal (I_{sheet} and C_{sheet}), including the impacts and costs of sheet metal material production, lubrication, and any galvanization. The impacts and costs of die making are amortized over the total number of parts made on the die-set (N). In addition, the costs associated with the labor (including overhead) and equipment depreciation are also included. Table 3 presents the intrinsic impacts and costs (per kilogram of metal, per kilowatt hour of electricity, etc.) used to complete the case study analyses. The derivation of these impacts and costs is discussed below.

The environmental impacts of producing electricity were modeled using ecoinvent 3.1 medium voltage database entries for the USA averaged by production volume. The cost of electricity was taken as the average industrial electricity price in the continental USA in November 2014 [28].

Ecoinvent 3.1 contains database entries for low-carbon cold-rolled steel sheet and a generic sheet aluminum wrought alloy. Table 3 includes both these values as well as the calculated impacts for the specific alloy (AA6014) used in the case studies. The impacts of the AA6014 alloy were modeled using ecoinvent 3.1 for the aluminum and most alloying elements, and the Idemat database for vanadium. The composition of the alloy was taken from The Aluminum Association's "Teal Sheets."

For all the sheet metal materials, ecoinvent 3.1's value for recycled content (r%) was used. For the case of steel sheet, the lack of any electric arc furnace processing (used to melt scrap steel) in the ecoinvent 3.1 entry appears to be an arbitrary artifact of the modeling database as there is no discussion on it in the ecoinvent documentation, and the final impact values for steel sheet suggested by the ecoinvent are within the range of other sources that model the recycled content between 20% and 42% [15,24,29]. As such, the ecoinvent 3.1 entry was not updated.

Ecoinvent 3.1 contains an entry for galvanization of steel sheets and is used, unchanged, in this analysis. The forming process requires a small amount of lubricant, modeled using ecoinvent's "Lubricating oil" entry, which assumes a lubricant derived from diesel. The costs of new and scrap sheet metal were derived from Ashby [24] and interviews with a range of U.S. scrap merchants.

Interviews with a range of car and die-makers suggested an average labor cost for stamping of \$65/h (including overheads) and that an appropriate cost for a new 1100 ton hydraulic press would be \$2.5 million. Assuming a 15 year write-off period, linear depreciation, and a potential utilization period of 4000 h a year, equipment depreciation is equal to \$42/h.

Case Study Results. The environmental impacts per part for the hood and tailgate are shown in Figs. 12 and 13, respectively. In both cases, the impacts from making the sheet metal dominate. The material yield from stock sheet to final part ranges from 56% (hood) to 31% (tailgate); therefore, a significant quantity of the overall impacts is represented by sheet metal that is scrapped due



(a)



(b)

Fig. 11 Stamped aluminum case study parts: (a) aluminum hood (hydraulic press) and (b) aluminum tailgate (mechanical press)

to blanking and trimming the final part. In contrast to the sheet metal and die-set, impacts from the press electricity are less than 1% of any impact category, and the impacts of the lubricant account for less than 0.1% of any impact category.

The relative importance of the different inputs change depending on the impact category. Sheet metal is the most dominant for human health impacts because of the toxic substances used in metal mining and refining. For example, a toxic red mud is produced in the Bayer process (for refining aluminum ore).

The costs of forming the case study parts are shown in Fig. 14. Whereas the sheet metal dominates the environmental impacts, the die-set dominates the costs. The cost of sheet metal is still important but the rebate to the manufacturers from selling scrap reduces the overall financial burden. The cost of electricity, labor, and equipment depreciation are all negligible. This finding is in agreement with Poli [20] who asserts that due to short forming times the die and sheet metal account for the majority of costs.

A General Model for Stamping Impacts and Costs. The case study results show that the die-set and sheet metal dominate both environmental impacts and costs. Simple Eqs. (1) and (2) can therefore be used to approximate the impacts (I_{xx}) and costs (C_{xx}) of forming any (applicable) part.

$$I_{\text{per part}} \approx I_{\text{sheet}} + \frac{I_{\text{die}}}{N} \quad (1)$$

$$C_{\text{per part}} \approx (C_{\text{sheet}} - C_{\text{scrap}}) + \frac{C_{\text{die}}}{N} \quad (2)$$

The impacts and costs of the sheet metal (I_{sheet} and $C_{\text{sheet}} - C_{\text{scrap}}$) can be expressed as Eqs. (3) and (4), where X is the surface area (in square meters) of the formed part (one side), T is its thickness (in meters), α is the material yield (ratio of part mass to original sheet mass), and ρ_{metal} is the density of the sheet metal (in kg/m^3). The intrinsic impacts and costs of sheet metal production (i_{sheet} , i_{galv} and C_{sheet} , C_{scrap}) are given in Table 3. The material yield (α) may be known to the designer or can be assumed to be 0.52. This yield comes from an average blank to final part yield of 65% from Omar's study on car part production [26] multiplied by an assumed blanking yield of 80%.

$$I_{\text{sheet}} = \frac{X}{\alpha} [T\rho_{\text{metal}}i_{\text{sheet}} + i_{\text{galv}}] \quad (3)$$

$$C_{\text{sheet}} - C_{\text{scrap}} = \frac{XT\rho_{\text{metal}}}{\alpha} (c_{\text{sheet}} - c_{\text{scrap}}(1 - \alpha)) \quad (4)$$

The impacts of die making can be calculated by multiplying the impacts shown in Table 3 by the cast die mass and mass machined. However, these masses are unlikely to be known early in the design process when only the geometry of the sheet metal part has been determined. In order to allow designers to predict the impacts of die-making, die-set and corresponding part data were collated from a Michigan die-maker and are shown in Table 2. The data were used to examine the relationship between the blank size (X/α_{trim}) and the mass of the zinc die-set, plotted in Fig. 15, and between the blank size (X/α_{trim}) and the cost of the zinc die-set, plotted in Fig. 16. α_{trim} is the ratio of the part mass to the blank mass. α_{trim} may either be known to the designer or assumed to be 0.65, pursuant to Omar.

The data shown in Fig. 15 suggest that the die mass is dependent on the size of the blank and independent of whether the blank is steel or aluminum. This finding is consistent with communications between this paper's authors and die-makers. A linear line of best fit (passing through the origin) has been added to the graph in Fig. 15. The equation of this line (shown in Eq. (5)) can be used to predict the mass of a zinc die-set given the blank area. This die-size can be multiplied by the intrinsic impacts of zinc die-making (shown in Table 3, $i_{\text{die-making}}$) in order to calculate I_{die} (Eq. (6)). If the mass of material removed by machining ($M_{\text{die-machined}}$) is unknown it can be assumed to correspond to 15% of the cast mass (M_{die}). With reference to Fig. 15, the following equation is valid for blank sizes up to 4.5 m^2 .

$$M_{\text{die}}(\text{kg}) = a \times \frac{X}{\alpha_{\text{trim}}}; \quad a = 4590 \text{ kgm}^{-2} \quad (5)$$

$$I_{\text{die}} = i_{\text{die-making}}M_{\text{die}} + i_{\text{die-machining}}M_{\text{die-machined}} \quad (6)$$

The cost (C_{die}) of the die can be estimated from the line of best fit shown in Fig. 16, expressed in the following equation:

$$C_{\text{die}}(\text{USD}) = \left(b \times \frac{X}{\alpha_{\text{trim}}} \right) + c; \quad b = \$4840 \text{ m}^{-2}; \quad c = \$35,270 \quad (7)$$

With reference to Fig. 16, Eq. (7) can be used to predict die costs for blank areas between 1 m^2 and 3.5 m^2 . However, Fig. 16 shows that there is only a weak positive correlation between blank size

Table 3 Intrinsic environmental impacts and costs

	Density (ρ_{metal})	CED	GWP	Human health	Costs	
Inputs: electricity ($i_{\text{electricity}}$)	N/A	MJ/kWh	kgCO _{2e} /kWh	DALY/kWh	USD/kWh	
Medium voltage	N/A	13	0.7	4.7×10^{-7}	0.07	
Inputs: sheet metal (i_{sheet} , C_{sheet} , C_{scrap})	kg/m ³	MJ/kg	kgCO _{2e} /kg	DALY/kg	USD/kg	USD/kg
Low carbon steel sheet ($r=0\%$)	7850	31.3	2.5	3.2×10^{-6}	0.71	0.32
Generic alum. sheet ($r=24.2\%$)	2700	180.3	15.5	2.1×10^{-5}	2.55	1.54
Aluminum sheet (AA6014, $r=24.2\%$)	2700	181.9	15.5	2.1×10^{-5}	2.55	1.54
Inputs: galvanization (steel sheets) (i_{galv})	Thickness	MJ/m ² sheet	kgCO _{2e} /m ² sheet	DALY/m ² sheet	N/A	
		(area of 1 side of sheet)	(area of 1 side of sheet)	(area of 1 side of sheet)		
Galvanizing impacts account for galvanizing on both sides of sheet	20–45 μm thick	82.1	5.3	1.8×10^{-5}	N/A	
Inputs: lubricants	kg/m ³	MJ/kg	kgCO _{2e} /kg	DALY/kg	USD/kg	
Lubricating oil	845	84.1	4.0	1.4×10^{-6}	5.5	
Inputs: die materials ($i_{\text{die-making}}$)	kg/m ³	MJ/kg	kgCO _{2e} /kg	DALY/kg	USD/kg	
Cast zinc ($r=97.5\%$)	6920	16.4	1.0	9.7×10^{-7}	N/A	
Inputs: machining die materials ($i_{\text{die-machining}}$)	kg/m ³	MJ/kg _{removed}	kgCO _{2e} /kg _{removed}	DALY/kg _{removed}		
Cast zinc	6920	10.4	0.6	3.5×10^{-7}		

(and hence die size) and die cost. The Michigan die-maker indicated that the fee charged to the customer just for casting the zinc (excluding any design, engineering, or machining costs) is \$0.45/lb (\$0.99/kg). Using this “pour fee” the fraction of the total die cost that can be attributed solely to the casting process was added to Fig. 16. It shows that in all cases the casting process accounts for less than 35% of the overall costs. It appears that the casting fee may be proportionally higher for larger die sizes. This may be because the designing and machining costs do not increase linearly with die size, unlike the casting fee.

In order to understand the other costs in die-making, the time taken to make a zinc die was evaluated by performing a “walk through” of the die-maker’s factory: starting at the office in which the die-making company receives CAD drawings of sheet metal

parts through to the warehouse containing finished prototyping dies ready to be delivered to the car companies. Interviews were conducted with the managers in charge of (1) tool design, (2) die-making, and (3) die try-out. They estimated the lead-time in each of the subprocesses they managed. The results are summarized in Table 4.

Table 4 indicates that 51% of the time taken to deliver a die-set is required for die design and try-out. It is therefore unsurprising that the casting (part of the die-making process) is not the main determinant of the overall cost.

Should Engineers Focus on Improving Die-Making or Reducing Sheet Metal Scrap? The case studies highlight that the sheet metal and die-sets dominate the environmental impacts and

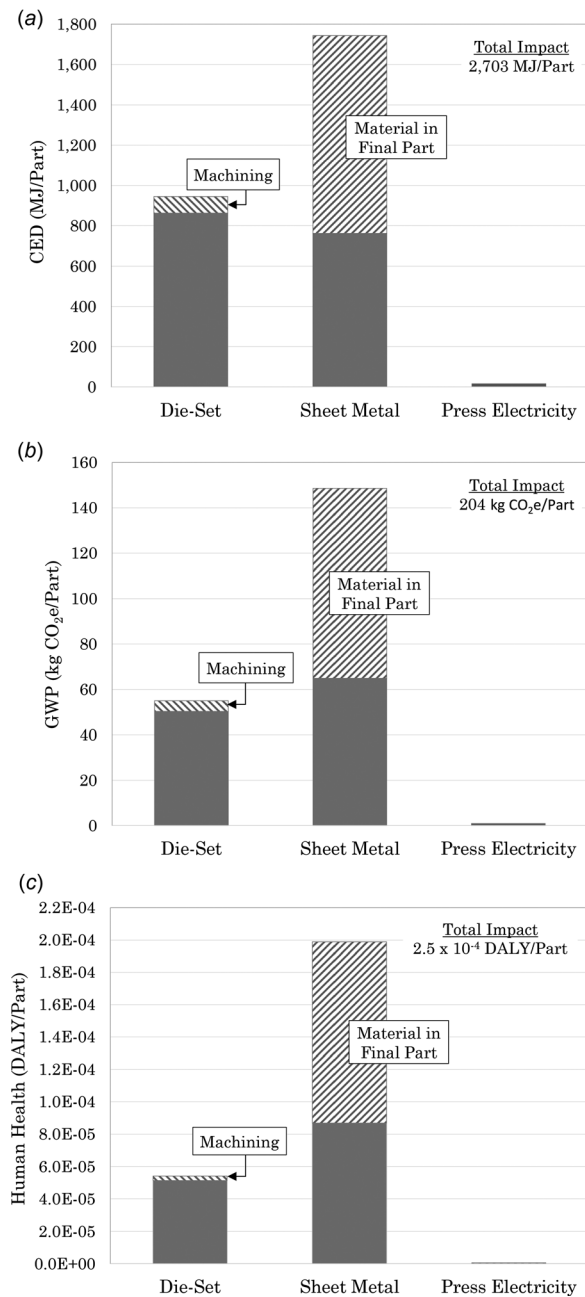


Fig. 12 Environmental impacts from the hydraulic press (truck hood) case study: (a) CED, (b) GWP, and (c) human health impact

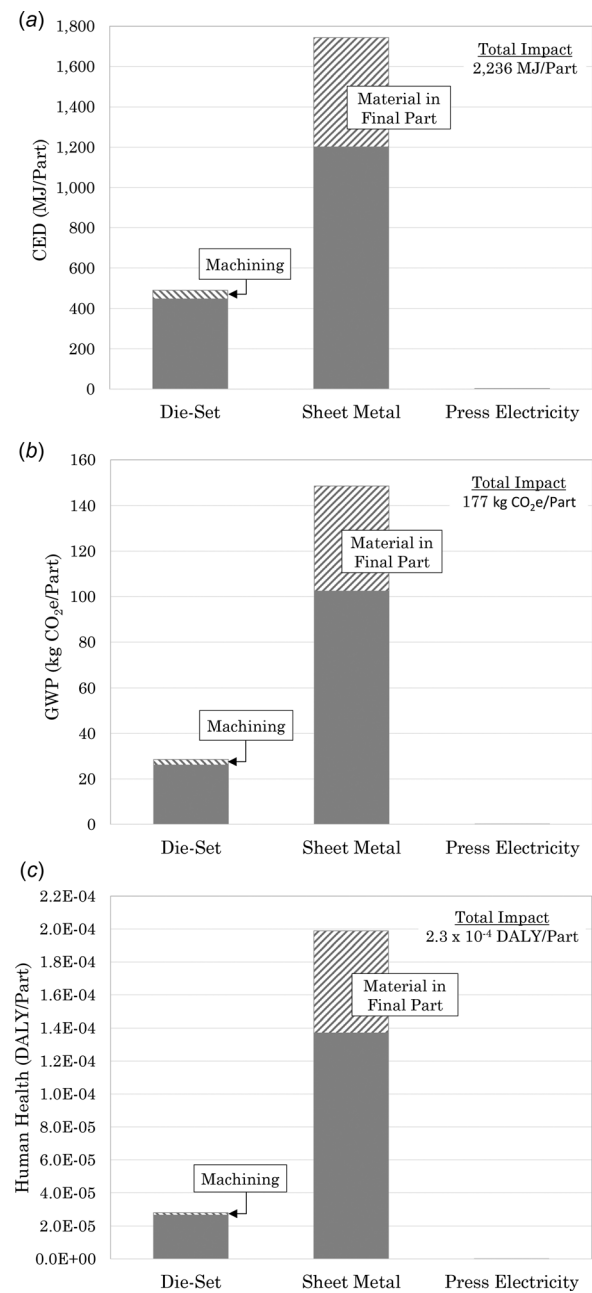


Fig. 13 Environmental impacts from the mechanical press (truck tailgate) case study: (a) CED, (b) GWP, and (c) human health impact

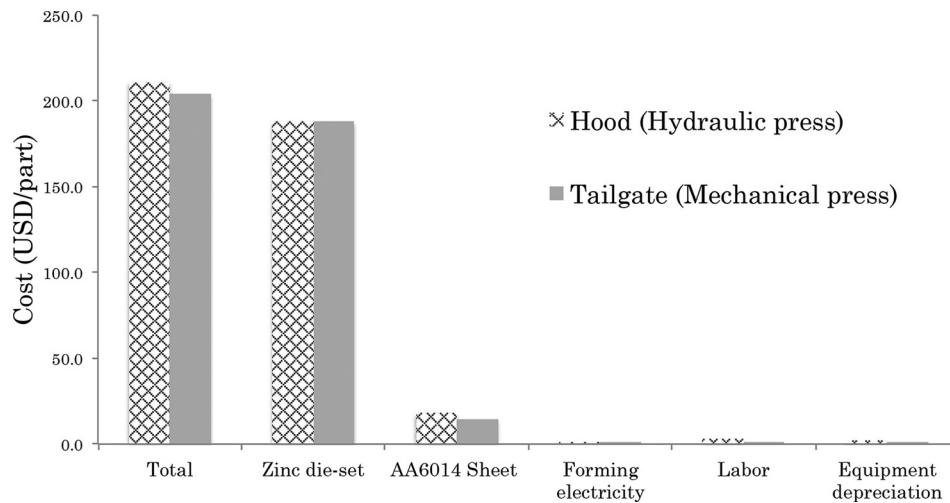


Fig. 14 Case study costs

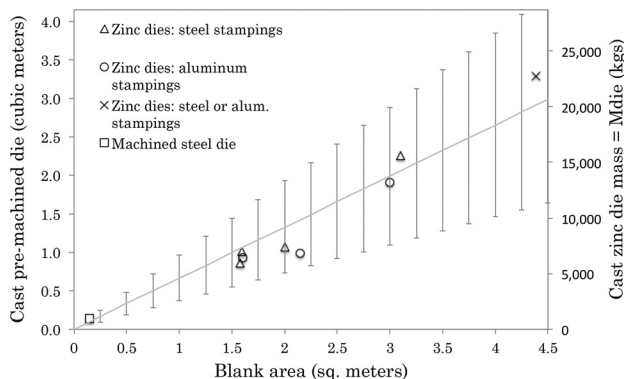


Fig. 15 Blank area versus die size. Error bars: $\pm 45\%$ of mass.

forming costs. In order to explore the importance of these two inputs, the generalized models presented in the last section (“A General Model for Stamping Impacts and Costs”) were used to predict the per part CED and costs for forming different batch sizes of aluminum parts with a part surface area (one-side, X) of 1.5 m^2 and thickness (T) of 0.0015 m (1.5 mm). The results are presented in Fig. 17, showing that for batch sizes greater than 90 parts the sheet metal dominates the CED requirements; whereas,

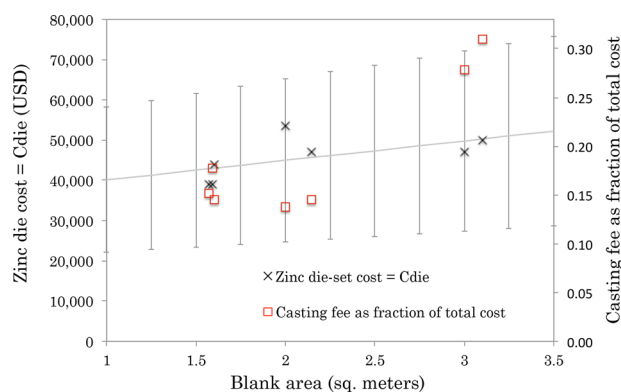


Fig. 16 Blank area versus die cost. Error bars: $\pm 45\%$ of cost.

the die-set dominates the costs for all applicable batch sizes (a zinc die is likely to need replacement after 1000 parts). The die-set’s dominance in cost but not CED may be due to the relatively high efficiency (low $\text{USD}/\text{MJ}_{\text{invested}}$) with which commodity sheet metal is produced. In comparison, bespoke die-set manufacturing requires extensive manual labor and engineering time, and thus, the costs are high compared to the energy invested (high $\text{USD}/\text{MJ}_{\text{invested}}$). The dominance of die-set costs, including the long lead times the costs reflect, for small batch production of sheet metal parts explains recent interest in die-less forming technologies such as incremental sheet forming. In contrast, engineers interested in reducing environmental impacts (especially at high batch sizes) should focus on reducing sheet metal scrap losses.

Discussion

In this section, opportunities that could lead to cheaper and “greener” sheet metal forming are highlighted.

Opportunities to Improve the Die-Making Process. The study at the Michigan die-makers highlighted three opportunities to improve the process: (1) ensuring a high furnace efficiency

Table 4 Lead time for making a generic zinc stamping die

Process	Lead time for each die-set unit (h)		
	Post	Ring	Female
Tool design	66 total across the die-sets		
Draw development	30		
Finite element analysis of draw	20		
Die geometry design (CAD)	10		
NC machining programming	2	2	2
Die-making	120 total across the die-sets		
Machining patterns	5 total across the die-sets		
foundry casting (making molds and pouring zinc)	24 total across the die-sets		
NC machining (base, rough and final)	18	12	24
Die construction	16	4	16
Try-out	60 total across the die-sets		
Total	246 h \approx 3 weeks @ two 8-h shifts per day for 5 days per week		

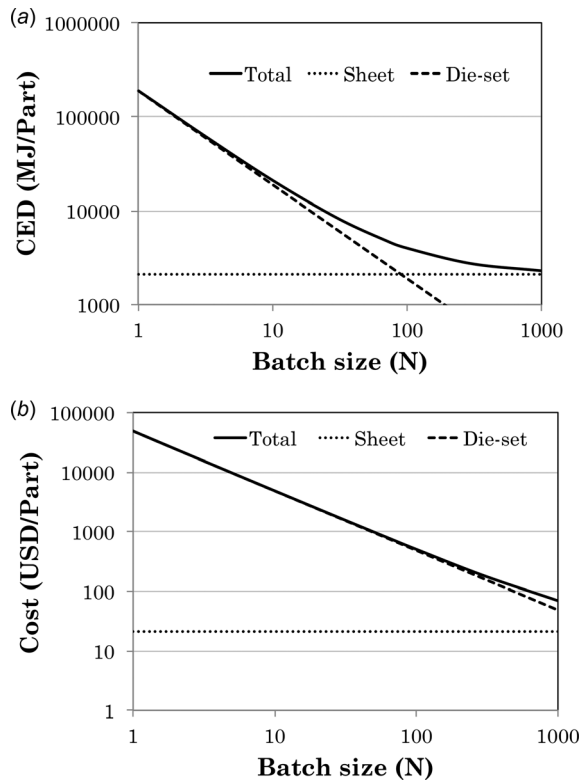


Fig. 17 The CED and cost for stamping an aluminum part: 1.5 m² surface area, 1.5 mm thick: (a) CED and (b) cost

when casting zinc; (2) greater in-house recycling of large die-sets and machining chips; (3) reduction in hand finishing of die-sets and shorter die try-out times in order to reduce costs.

The annual energy efficiency of the foundry ranged from 0.13 therm_{gas}/kg_{zincpoured} in 2008 to 0.03 therm_{gas}/kg_{zincpoured} in 2013. Even in 2013, the efficiency of the furnace was only 10% (the theoretical minimum energy required to melt zinc is 2.6 therm_{gas}/tonne). Efficiency could be increased by grouping work projects together with longer idling times between the work periods, allowing the furnace to be shut down.

The material flow model shown in Fig. 1 shows that a considerable amount of recycled material must be remelted twice in order to make a new die-set: once at the external foundry to make an ingot and again at the die-maker. One of these melting cycles could be avoided by breaking the larger die-sets in order to allow them to fit in the smaller furnaces and investing in ventilation equipment in order to allow remelting of the lubricant covered chips. These alterations could reduce the CED of die making by between 8 and 20% depending on the ability to reduce dross losses.

Die-sets dominate the cost of small batch metal forming. Figure 16 shows that the casting process accounts for less than a third of the overall costs, and Table 4 shows that a quarter of the time is taken up by labor-intensive die try-out, which includes repeatedly producing practice parts and sanding/grinding the die surfaces to ensure that the sheet metal does not split or wrinkle. Further advances in forming finite-element modeling may allow the final die-shape to be achieved by machining alone.

Opportunities to Reduce Press Electricity Demand. The hydraulic press requires considerably more electrical energy than

the mechanical press (1.2 kWh/part versus 0.2 kWh/part in the case studies). This is partly because the hydraulic press has a much higher standby power (19 kW versus 3 kW); the fixed speed motors continue circulating hydraulic fluid even during idling or low speed jogging. As energy use is proportional to the cube of the flow rate in the hydraulic system this leads to large energy requirements.

Motor speed control offers the potential for energy savings in hydraulic systems. This is likely to be particularly relevant in prototype and low volume production with long periods of standby power requirements. Possible solutions include DC motors where the voltage supply level can be adjusted, or electronic adjustable-speed drives (ASDs). These devices could save energy by slowing a motor to match light loads. There is evidence that in some new machines and recent retrofits metal formers are taking advantage of motor speed control drives [30].

Regarding mechanical presses, over the last decade press builders, mainly in Japan and Germany, have developed mechanical servo press technology that replaces the conventional flywheel, clutch, and brake with a servomotor. A servomotor can recover kinetic energy during deceleration and store this energy in a capacitor or independent flywheel in order to use it during the next stroke. In addition, high impact loads can be avoided, increasing tool life. Osakada et al. provide a comprehensive analysis of servopress technology in metal forming applications [31].

Opportunities to Reduce Sheet Metal Impacts. The sheet metal material yield may be improved by tessellation (nesting) of the blank shapes on the original sheet metal. This is already done during mass production but is often not considered during prototyping or low volume production. Alternatively, there may be opportunities to use the scrap generated to make smaller products. For example, Abbey Steel in the UK is a company that buys automotive steel scrap in order to make small electrical boxes [32]. Finally, solid mechanics research projects could focus on eliminating/reducing the need for blanks significantly larger than the final part (which currently leads to the excess material that must be trimmed).

Conclusions

In this study, we have presented cradle-to-gate environmental impact and cost analyses for making sheet metal parts, including the first study on zinc die manufacturing. The case studies show that the electricity required to operate a forming press has insignificant environmental impacts and costs compared with the sheet metal transiting through the process or (for low-to-medium sized batch sizes) the die-sets used to form the sheet metal. This finding suggests that the focus on making sheet metal forming more environmentally benign should shift away from looking at the forming presses and instead look toward reducing impacts in die production and improving the sheet metal material yield.

Acknowledgment

This work has been supported by U.S. Department of Energy grant: DOE/EE-0998. We are grateful to all the foundries, die-makers, and car companies for the data they provided.

Appendix: Inputs Into Simapro for Impact Modeling of Cast Premachined Zinc Die.

Both Ecoinvent 3.1 furnace entries were modified to include U.S. natural gas instead of ROW-worldwide average

Output: premachined zinc tool	1	kg	Zinc die after dross and gates removal (90% of poured mass)
Inputs (ecoinvent 3.1 entries)			
Purchased zinc from external foundry: Recycled content and material production impacts			
Primary zinc: zinc {GLO} market for Alloc Rec, U	0.028 ^a	kg	Primary zinc $I/P = (1 - \text{die recycled content})/0.9$
Secondary (remelter) zinc: U.S._Heat, district or industrial, natural gas {RoW} heat production, natural gas, at industrial furnace low-NOx > 100 kW Alloc Rec, U	0.016 ^a	therm	Furnace at external foundry (1 therm = 106 MJ; CED of natural gas = $1.47 \times \text{energy content}$) $106 \times 1.47 = 155.1$ $I/P = (10/155.1) \times (0.25 - (1 - \text{die recycled content}))/0.9$
Zinc sand casting			
U.S._Heat, district or industrial, natural gas {RoW} heat production, natural gas, at industrial furnace low-NOx > 100 kW Alloc Rec, U	0.06 ^b	therm	On-site furnace $I/P = 0.05/0.9$
Mold making			
Silica sand {GLO} market for Alloc Rec, U	0	kg	Neglected
Activated bentonite {GLO} market for Alloc Rec, U	0	kg	Neglected
Water, unspecified natural origin/kg	0.207	kg	No recycling (evaporates). Zinc sand mixture usage \times zinc water fraction/0.9
Polystyrene, expandable {GLO} market for Alloc Rec, U	0.003	kg	$I/P = (16/6920)/\text{foam mold fabrication Yield}/0.9$
Electricity, medium voltage U.S. Ave market for Alloc Rec, U	0.218	kWh	Mold making (1 therm = 29.3 kWh) $I/P = (0.06 \times (7/55) \times 29.3)$
Inert waste {GLO} market for Alloc Rec, U	0.000	kg	Sand and bentonite use neglected
Waste polystyrene {CH} treatment of, sanitary landfill Alloc Rec, U	0.003	kg	
Parameters			
Zinc sand mixture usage rate (kg/kg metal cast)	5.5		Dalquist and Gutowski [22]. Only used to determine water consumption rate.
Zinc water fraction	0.034		Provided by Michigan die-makers
Foam mold fabrication yield	0.750		Estimate based on observations in Michigan.

^aFor a recycled content of 97.5%.

^bAverage furnace efficiency.

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