The energy requirements and environmental impacts of sheet metal forming: an analysis of five forming processes

Daniel R Cooper^{1§}, Kathleen E Rossie², and Timothy G Gutowski²

¹University of Michigan, 2458 George G. Brown Laboratory,
2350 Hayward, Ann Arbor, MI, USA, 48109-2125

²Massachusetts Institute of Technology, 77 Massachusetts Avenue, Room
35-234, Cambridge, MA, USA, 02139

[§]Corresponding author, email address: drcooper@umich.com

Abstract

Industrial emissions must be dramatically reduced to avoid the potentially dangerous effects of climate change. In order to contribute to the necessary cuts, this article focuses on the energy and material efficiency of sheet metal forming. The processes considered include traditional methods, such as drawing and stretch forming, and newer technologies developed in recent decades such as hydroforming (fluid cell forming), superplastic forming, and incremental sheet forming.

In this analysis, we conduct case studies on forming processes at leading US car and aerospace manufacturers. The case studies include electrical power measurements on the forming machines and also consider the impacts of making the dies, sheet metal, and lubricant. Cradle-to-gate energy demands and environmental impacts are modeled in SimaPro using data based on ecoinvent 3.1 database values. The results show that idling consumes significant electricity; however, other than for incremental forming, the impacts of press electricity are small compared to the impacts of making the sheet metal. The case studies inform generalized models for each process that allow per part impacts to be estimated based only on final part material, size (surface area, thickness,

and depth), and the number of parts produced over the die-set lifespan. The models are used to investigate the potential to reduce cradle-to-gate energy requirements by using incremental forming instead of drawing to form parts. It is found that there are significant potential savings for small production runs, consistent with part development/prototyping. However, these savings vary depending on the part size and the relative buy-to-fly ratio (material yield) of the two processes.

The results of this study highlight that for small production numbers over the die lifespan the impacts of die-making are important. However, as production numbers increase above one hundred parts per die-set, the impacts of making the sheet metal become dominant. It is therefore concluded that researchers interested in reducing the environmental impacts of sheet metal forming concentrate on innovations that would reduce sheet metal blanking and post-forming trimming losses.

Keywords: Metal forming, incremental sheet forming, drawing, stamping, stretch forming, hydroforming, flexforming, fluid cell forming, superplastic forming, energy efficiency, material efficiency, environmental impacts

1 Introduction

The Intergovernmental Panel on Climate Change has recommended that global emissions be cut by 40-70% from 2010 levels by 2050 if we are to avoid the worst consequences of climate change (IPCC, 2014). Allwood et al. (2010) have shown that if industry fails to match these cuts, reaching the overall target is likely unfeasible. It is therefore incumbent on engineers to examine ubiquitous industrial processes, such as sheet metal forming, in order to highlight potential energy and material efficiency improvements.

The forming of complex sheet metal parts is expensive and requires energy-intensive inputs. The sheet parts are typically made from steel or aluminum, and production of these two metals accounts for over 10% of global anthropogenic carbon dioxide emissions (Allwood et al., 2012). Work by Cullen et al. (2012, 2013) suggests that as much as one fifth of the metal produced (corresponding to 2% of global emissions) is cold rolled into thin sheets for subsequent forming. Additionally, forming processes typically use part-specific die-sets that require energy-intensive casting and machining operations to manufacture. The dies are then pressed into the sheet using mechanisms that rely on electric motors that are often poorly optimized to the load characteristics during the forming cycle (Zhao et al., 2015).

Despite the prevalence of sheet metal forming in industry, relatively little work has been done on examining the energy demands and environmental impacts of forming. A rare example would be Milford et al. (2011). They examine potential forming improvements to the stamping of a steel car door (increased process energy efficiency, material efficiency, and light weighting), finding lifecycle energy savings of between 1% and 11%. This article focuses on five common sheet metal forming processes: drawing, stretch forming, hydroforming (specifically, fluid cell forming),

superplastic forming, and incremental sheet forming. Figure 1 presents a schematic of each process. A brief description of each process and its relevance to industry is given below.

Figure 1: Schematics of the five forming processes

Drawing, often referred to as the more generic stamping, is an established forming technology that has been used since the late 19th century (Hounshell, 1984). In drawing, parts are formed from flat, often non-rectangular sheet metal blanks. Drawing is used to make appliance panels (oven tops, metal sinks, etc.) and many parts in the car industry such as hoods, doors, and fenders (Omar, 2011). Drawing requires matched profile

male and female dies (often referred to as the punch/post and die respectively) that are pushed together to form the final shape (Lange, 1985). 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 to help minimize springback) as it is drawn into the cavity of the female die (Tschaetsch, 2006). There is minimal thinning of the sheet as the periphery of the blank is ‘drawn-in’ to the die rather than being rigidly clamped (Tschaetsch, 2006). The periphery of the formed part will, however, typically need to be trimmed to produce the final shape. Drawing is ubiquitous when complex sheet metal parts are mass-produced (Hirt and Bambach, 2012) because it is a fast process and material handling is relatively simple. High upfront tooling costs have, however, helped motivate the development of forming processes with lower tooling requirements, discussed below (Hirt and Bambach, 2012).

In sheet stretch forming, which dates back to the early days of metal aircraft manufacturing, a rectangular blank is gripped on two opposing sides and stretched over a single male die (Kalpakjian and Schmid, 2013). The process variant analyzed in detail in this article is ‘drape’ stretch forming, in which the blank is clamped in grippers which are set to an appropriate angle in relation to the die (Parris, 1996). During forming the die moves and pushes into the blank. This net thinning process requires the clamped regions of the sheet (and excess on either side of the die) to be trimmed to produce the final shape. Stretch forming has low upfront tooling costs (Wang et al., 2014) and is often used to produce large parts with shallow contours; for example, it is used extensively in the aerospace industry to make parts like fuselage panels (Parris, 1996; Kalpakjian and Schmid, 2013) and other components too large to be made with competing technologies such as hydroforming (Lange, 1985). Stretch forming cannot be used, however, to form detailed features into the sheet.

Hydroforming refers to a family of processes in which a liquid is pressurized on one side of the blank, forming the metal against a single

stationary die. The process variant analyzed in detail in this work is fluid cell forming, often called flexforming (Koç, 2008; Hatipoğlu et al., 2010). In fluid cell forming (FCF), the pressurized fluid is contained within a rubber bladder situated above a tray that can be filled with multiple dies. Before forming, flat (often non-rectangular) sheet metal blanks are placed, or clipped, on top of the dies. The bladder is then pressurized and envelops the whole tray, meaning that multiple parts can be formed simultaneously in each forming cycle. As with drawing, there is minimal thinning of the sheet during forming because the blanks are not rigidly clamped. Dies commonly have a male or female profile with a raised perimeter around the outside of the die that acts as a blank holder during forming (Koç, 2008). Blank holding suppresses wrinkling and springback, but means that the periphery of the part will have to be trimmed to produce the final shape. Alternatively, dies may have a male profile with no raised perimeter. In this case, the bladder wraps the blank around the die and net-shape forming may be achieved with no trimming of the formed part necessary (Koç, 2008). During FCF, the pressurized bladder and stationary die impose a hydrostatic pressure on the sheet, which has been shown to improve formability (Lange, 1985). FCF is often used to produce small to medium sized batches of parts in the aerospace industry, as well as car part prototypes and components for specialty vehicles, particularly when these components are difficult to draw (Tschaetsch, 2006). FCF development began in the mid-20th century, but improved process control has resulted in increased use since the 1990s (Koç, 2008).

Superplastic forming (SPF) can be used to form certain aluminum, titanium, and magnesium alloys. In this study, the focus is on aluminum SPF, in which pressurized air is used to form a flat, rectangular sheet metal blank against a single die at an elevated temperature: 50-75% of the absolute melting temperature of the sheet (Liu et al., 2012). A pressure chamber situated above the die rigidly clamps the periphery of the blank. This rigid clamping prompts significant thinning during forming. The periphery of the formed part must be trimmed in order to make the final

part shape. The blanks are made from specific superplastic alloys with a fine grain structure ($<10\text{ }\mu\text{m}$) that allows very high strains to be developed at the elevated forming temperatures (Langdon, 2013); a single superplastic forming process can often substitute multiple drawing (and annealing) processes needed to form a complex geometry (Friedman et al., 2004). SPF was developed to exploit this high formability; it was commercialized for military aircraft in the 1980s and expanded to commercial aircraft and other applications in the 1990s (Sanders, 2004). Superplastic sheet materials are typically expensive because they are produced in low volumes, contain expensive alloying elements, and require additional thermomechanical processing. For example, superplastic aluminum can be up to three times the price of conventional aluminum (Carpenter and Smith, 2002). Also, SPF forming times are long because the flow stresses within the hot sheet are sensitive to the imposed strain rate (Kazemi and Weber, 2013), typically restricted to 10^{-4} - 10^{-2} s^{-1} . SPF is often used to make small numbers of parts with a very complex geometry such as aircraft leading edges and strakelets (Rossie, 2015).

Incremental sheet forming (ISF) is used to form parts from flat, typically rectangular, sheet metal blanks that are rigidly clamped around the periphery, prompting significant thinning in the final part (Jackson and Allwood, 2009). The periphery of the formed part must be trimmed in order to make the final part shape. Forming is achieved using one or more tools (typically solid hemispherical indenters) that trace out a tool path while pushing into the blank, progressively forming the three-dimensional shape. Tooling configurations, reviewed by Hirt and Bambach (2012), range from single point incremental forming (SPIF), in which an indenter is only present on one side of the sheet, to double-sided incremental forming (DSIF), in which indenters are present on both sides of the blank and can squeeze as well as indent the metal. There is some evidence of ISF variants being used for low volume production by Japanese car makers (Tschaetsch, 2006) and in small workshops and private enterprises (Jackson and Allwood, 2009). However, since its inception in

the early 1990s, ISF has seen limited adoption outside of research institutions, partly because of slow forming times and poor surface quality (Lamminen et al., 2004), as well as the poor dimensional accuracy of the final part (Allwood et al., 2005). Despite these issues, interest in the process has remained high because it offers low (or no) tooling cost and short (or no) lead-time before production can begin. In addition, ISF may be able to improve formability: Jackson and Allwood (2009) showed that ISF promotes through thickness shearing of the sheet and Allwood and Shouler (2009) found evidence that superimposed shear lifts the forming limit diagram, allowing larger surface strains. A recent collaboration jointly funded by a leading US car company and the US Department of Energy has seen extensive research into overcoming the above issues and the construction of the largest ISF machine to date. Case studies on this ISF machine form the focus of this paper's contribution to research on ISF.

A review of the previous work on the energy and environmental impacts of sheet metal forming is given in Section 2, and informs the current paper's scope.

2 Review

There have been few holistic studies on the environmental impacts of sheet metal forming. Studies that examine the energy required to make a sheet metal part typically ignore the energy invested in making the sheet metal and lubricant, and in the die-making process. In a sustainability orientated analysis, Ingarao et al. (2012) state that in sheet metal forming, unlike in machining, there is little “material wastage” and therefore the electrical consumption of the press is the dominant factor to analyze when establishing environmental impacts. However, in a study on the car industry Omar (2011) finds that on average 35% of the material in a sheet metal blank does not make it into the final part and is scrapped. The impacts of wasted material should not, therefore, be assumed negligible. In an environmental and cost analysis of stamping low volume sheet metal car parts, Cooper et al. (2016) find that the impacts of the press electricity are negligible when compared to the impacts of the sheet metal or die-making process.

2.1 Die-set and sheet metal impacts

Many researchers make die-set cost comparisons between an emerging technology (FCF, SPF, or ISF) and conventional drawing. In the case of FCF, Peltier and Johannisson (1998) state that the process leads to a 50-90% reduction in tool costs compared to drawing. In a study on the production of aluminum door structures, Luckey et al. (2007) find tool savings of 80% for SPF compared to drawing. Friedman et al. (2004) also compare SPF (in this case of aluminum car hoods) to drawing, finding that SPF is cheaper for batch sizes smaller than 5,000 parts. Despite the apparent cost savings associated with FCF and SPF in the above studies, it is unclear whether these savings correspond to energy savings or a reduction in environmental impacts.

Regarding ISF, Ingarao et al. (2012) suggest that using the process could lead to 10% sheet metal material savings compared to conventional drawing because “the shapes are obtained exclusively by stretching mechanics.” However, existing ISF machines have discrete rectangular frame sizes that prevent optimization of the blank shape and size. For example, the trimming yields (final part-to-blank ratio) for the cones and pyramids formed as part of Dittrich et al.’s work are 15% (Dittrich et al., 2012), in comparison to an average trimming yield of 65% in stamping of car parts (Omar, 2011).

2.2 Electricity impacts

A few studies consider the electrical energy needed to form sheet metal. Examples include Zhao et al. (2015) and Cooper et al. (2016) for the case of hydraulic drawing presses, and Branker et al. (2012) and Ingarao et al. (2013) for the case of ISF. Electrical power measurements can at a minimum help engineers select appropriate motor sizes. Power measurements can also inform new machine architectures as designers look to minimize electricity costs and environmental impacts. Despite their utility, no electrical power measurements have been found in the literature on stretch forming, FCF, or aluminum SPF.

Several researchers report the electrical energy needed to operate a drawing press. Some express the energy needed per stroke of the forming press (Schuler, 1998; Zhao et al., 2015), and others the energy needed per kilogram of sheet formed (Brown et al., 1985; Burnham et al., 2006; Sullivan et al., 2010; Milford et al., 2011). Cooper et al. (2016) find that a hydraulic single-action press used for prototyping (800 short ton capacity) requires 1.2 kWh of electricity per stroke of the press. The electricity required per stroke is largely independent of the die geometry and material being formed. Subsequently, Cooper et al. deem “electricity requirements per stroke” an appropriate expression of electricity requirements in a hydraulic drawing press. In mass production

mechanical drawing presses are more commonly used. These presses are quicker than hydraulic presses and consume 0.1-0.2 kWh of electricity per part (Schuler GmbH, 1998; Cooper et al., 2016).

Several researchers find ISF machine electrical power requirements to be largely independent of changes in tool speed or incremental step size (Ingarao et al., 2013; Branker et al., 2012). Instead, the baseload power (minimum power required by the machine when on but not in use, frequently referred to as standby mode or idling) dominates the total power requirements (Dittrich et al., 2012; Branker et al., 2012) and the forming time determines overall electricity requirements (Branker et al., 2012; Ingarao et al. 2013). The largest power requirement of an ISF machine identified in the literature is 3 kW (Ingarao et al., 2013).

2.3 Scope of this paper

In light of the above review, this work focuses on measuring the electrical power draw of each process and then evaluating overall energy requirements and environmental impacts by considering the other inputs to the process: sheet metal, lubricants, and die-sets. In Section 3, case studies are conducted on each forming process. The results are used to identify the significant factors that determine the impacts of each process. Subsequently, global models are constructed in Section 4 that allow the impacts of making any (applicable) part using any of the five processes to be predicted. The models are used to examine the metered electricity consumption of the processes and the effect of producing different numbers of parts (over the course of the die-set lifespan) on the per-part energy intensity of each process. The potential to save energy by using ISF rather than drawing is also examined.

The energy demands and environmental impacts are modeled in SimaPro, a software package by PRé Consultants used to manage lifecycle inventory compilation (material flows, energy flows, and environmental releases) and the impact assessment process (SimaPro, 2016). Where case study

specific information is not available, lifecycle inventories are determined using data based on ecoinvent 3.1 database values, which contains inventory information from a variety of sources such as trade groups and previous scholarly work (Ecoinvent, 2016).

Impacts are calculated from lifecycle inventories via the use of impact assessment methodologies, which use scientific knowledge to connect consumption and emissions with specific types of environmental and health degradation. The impacts considered in this paper are 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). CED values are determined using Version 1.09 (August 2014) of the CED Method, and GWP and DALYs are determined using IMPACT2002+ Version 2.12 (PRé Consultants, 2013).

The boundaries of the analyses are shown in Figure 2. The impacts are expressed “per part” with the impacts of a die-set amortized (allocated equally) over the total number of parts produced using that die. The analyses are ‘cradle-to-gate’ life cycle assessments: the analysis starts from resource extraction (e.g., mining of ore, drilling for natural gas) and ends at the output of the forming process. In order to reduce confusion, in this paper ‘MJ’ refers to the CED, and ‘kWh’ refers to metered electricity use.

The ‘recycled content’ method (also known as the ‘cutoff’ approach) is used for all analyses. With this approach, the fraction of recycled material in the material inputs, along with the impacts of primary and recycled (secondary) material production, is used to produce ‘blended’ impacts for each material input (see Table 3). In the recycled content method, all metal scrap sent for recycling does not take any burden, nor does it receive any credit (Ashby, 2012). A lower process material yield will, however,

result in more material inputs being required for the same output. The ‘recycled content’ approach contrasts with the ‘avoided burden’ / ‘end-of-life’ approach where all input material is treated as being derived from primary production regardless of its true source. A credit equal in magnitude to the avoided primary material is then given for any scrap sent to recycling (Ashby, 2012). Use of the ‘recycled content’ and ‘avoided burden’ methodologies often results in only small numerical differences in impacts. The ‘recycled content’ approach has been deemed most suitable for this paper because consistent data on recycled content could be determined. Additionally, as demonstrated by Frischknecht (2010), the ‘recycled content’ approach reflects a “strong” sustainability perspective because environmental impacts are accounted for when they occur and scrap stocks are not assumed to be a replacement for natural ore stocks. A limitation of this approach is that manufacturers are not “rewarded” for choosing to recycle. However, all of the scrap in these analyses is routinely recycled for its economic value anyway.

Figure 2: Boundaries of analyses. i=impacts, see Table 3

The forming processes examined in this study are not perfect substitutes for each other. For example, simple stretch forming cannot be used to make sharp concave features on the outside of parts, whereas SPF, which can produce complex shapes in one process step, cannot be used to produce parts at the same rate as matched die-set drawing. If designers wish to directly compare the impacts of one process to another they should

consider the different capabilities of each process. Although not the focus of this work, Rossie (2015) examines the varying capabilities of each process by undertaking extensive literature reviews combined with semi-structured interviews with industry experts. Process descriptions and capability tables are available in Rossie (2015).

The work presented in this paper should be useful to press designers looking to improve the electrical efficiency of their equipment; to car, aerospace, appliance, and other companies looking to understand and minimize the impacts of their forming activities; and to researchers looking to understand where sustainability efforts should be focused in sheet metal forming.

3 Case studies on forming parts

Case studies were conducted at leading car and aerospace manufacturing companies based in the United States. The companies granted permission for conducting the case studies on the condition of anonymity.

3.1 Methodology

Case studies were conducted on each of the five forming processes. Figure 3 shows the parts made; Table 1 summarizes the key features of the parts and the die-sets used to produce them. The drawing case study was based on an analysis described in Cooper et al. (2016). Zinc die-sets were used in both the drawing and stretching case studies. Zinc is appropriate for low volume production in the hundreds or low thousands of parts because it is easier to cast and machine than iron but wears more quickly. FCF is the only process in which multiple parts can be made simultaneously. In the case study two FCF parts were produced at once; hence their inclusion in Table 1 and Figure 3. Table 1 also includes the production number over the die lifespan and the batch size (number of parts made sequentially until the next die-set changeover). The production number (N) is used to amortize the impact of die-making over the number of parts produced. The batch size (B) is used to amortize the impacts of batch set-up (for example, pre-heating the SPF die) over the number of parts in the batch.

The production number over the die lifespan (N) may be determined by either physical or economic factors. For instance, zinc drawing dies are likely to wear out and need replacement after being used to make several hundred parts (physical factor), whereas the number of parts made using long-lasting iron SPF dies is likely to be constrained by customer demand (economic factor). The batch size (B) is determined by internal company scheduling which may be influenced by customer demand. For example, aerospace customers may only require tens of units per year of some

aircraft parts, necessitating the manufacturer to either form small batches of parts or stock inventory.

Figure 3: Case study parts. The dotted red line in (e) denotes the periphery of the final part

Process	Part made	Product-ion number over the die lifespan (Parts/Die)	Batch size (Parts/Batch)	Part description						Lubricant		Die-set	
				Material	Stock sheet area (m ²)	Blank area (m ²)	Blank thickness (mm)	Final part area ¹ (m ²)	Final part mass (kg)	Type	Mass (grams/m ² blank)	Material	Mass (kg)
Drawing (750 short ton load)	Truck hood prototype	250	250	Alum. (AA6014)	3.70	3.00	0.95	2.10	5.4	Lubricating oil	0.75 (both sides)	Zinc ²	13,190 cast ³ 1,980 machined-away ⁴
Stretch forming	Large 'U' shaped part	750	8	Alum. (AA7075)	2.14	2.14	0.81	1.87	4.1	Lubricating oil	100 (one side)	Zinc ²	4,099 cast 410 machined-away
Fluid cell forming (30 MPa pressure)	Flanged rectangular part	750	750	Alum. (AA7075)	0.39	0.39	1.6	0.39	1.67	Lubricating oil	0.5 (both sides)	Alum. (AA7075)	92.8 block 18.6 machined-away
	Flanged semi-circular part	750	750	Alum. (AA7075)	0.04	0.035	1.6	0.035	0.15	Lubricating oil	0.5 (both sides)	Alum. (AA7075)	26.1 block 11.2 machined-away
Super-plastic forming	Semi-truck bumper	750	90	Alum. (SP5083)	3.30	3.30	3	1.92	15.5	Graphite	160 (one side)	Cast iron	4,897 cast 331 machined-away
Incremental sheet forming	Truncated cone ⁵	N/A	3	Low carbon galvanized steel	0.30	0.25	1	0.07	0.55	Lubricating oil	100 (both sides)	N/A	N/A

1. Final part area is approximate, as it assumes no thinning during forming
2. Zinc alloy: Kirksite A
3. The "cast" mass is the total die mass as-cast (minus the removal of any gates).
4. The "machined-away" mass is the mass of material removed by machining
5. Truncated cone: 300mm large diameter, 150mm small diameter, 80mm height. Corresponds to 'part 1' in Figure 4.

Table 1: Parts formed in the case studies

3.1.1 Forming equipment used in the case studies

Table 2 describes the forming equipment and process settings used in each of the case studies.

Process	Machine description
Drawing	Hydraulic single-action press with 800 short ton (726 t) capacity and forming area up to around 3 m x 3 m. The hydraulic system was replaced in 1999. Rams are powered by 75 HP (56 kW) and 60 HP (45 kW) motors both operating at 1200 RPM. The load during forming was 750 short tons (680 t).
Stretch forming	Drape forming TC500 Sheridan Gray machine with 500 short ton (454 t) capacity. The press can form parts from about 9 in. x 11 in. (0.23 m x 0.28 m) to about 15 ft. wide x 17 ft. long (4.57 m x 5.18 m). The maintenance manual dates to the late 1960s. The tool (die) bed motor is rated at 200 HP (149 kW) and the motor for clamping the grippers is rated at 75 HP (56 kW).
Fluid cell forming (FCF)	Verson press with a maximum forming pressure of 10,000 psi (69 MPa) and forming area of 157 in. x 43 in. (3.99 m x 1.09 m) and a maximum height of 7 in. (0.18 m). The press is estimated to be around 20 years old. The press is operated by six motors: two 75 HP (56 kW) motors operating 2 pumps and four 10 HP (7 kW) motors operating 5 pumps. The pressure during forming was 4,400 psi (30 MPa).
Superplastic forming (SPF)	Press with two heated platens and forming area of 6 ft. x 10 ft. (1.83 m x 3.05 m). The press dates to the early 2000s and is the facility's newest and largest press. Each platen has nine heating zones, with each zone containing twelve cartridge heaters. The inside three zones on each platen are rated at 19.2 kW and the outside six zones at 14.4 kW. A low pressure, high volume pump (30 HP, 22 kW, motor) opens and closes the press doors. A high pressure, low volume pump (10 HP, 7kW, motor) generates the clamping force. Two compressors provide the pressurized air for forming: one low pressure compressor rated at 125 HP (93 kW) and one high pressure compressor rated at 25 HP (19 kW). These compressors supply air to the entire plant, including multiple presses.
Incremental sheet forming (ISF)	A CNC controlled 8-axis machine with two 3-axis indenters on either side of the blank with additional horizontal spindles. The forming area of the machine is 2.0 m x 1.5 m with a potential forming depth of 0.475 m. This machine was recently installed (last three years) at a leading US car manufacturer.

Table 2: Description of machines used in the case studies. All machines supplied by 480 Volt, 3-phase, 60 Hz power supply

3.1.2 Electrical energy measurements

Electrical power measurements were taken using a Fluke 434 (Series ii) 3-phase power analyzer using a typical sampling period of one second. The active (real) power, power factor, and cumulative metered energy (in kWh)

were recorded. A minimum of three forming cycles was recorded for each process in order to provide reliable averaged results.

The real (or active) power performs work (or is converted to heat). The power factor measures the degree to which the voltage and current waveforms are out of sync and is equal to the ratio of the real power (consumed in the process) to the apparent power (the product of the root mean square voltage and current). A low power factor indicates increased heat losses (poorer efficiency) in transmission lines, transformers, and the load as the current flowing through the system is higher.

3.1.3 The environmental impacts of case study inputs

The intrinsic impacts of the electricity, material, and processing inputs to the case studies and generalized models are presented in Table 3 on an appropriate per unit basis (e.g., per kilogram of metal, per kilowatt hour of electricity, etc.). These values represent per unit impacts from cradle-to-the-boundary of this analysis (shown in Figure 2). Case studies (and predictive calculations) were completed by multiplying the per unit values in Table 3 by the actual input amount (e.g., a 2 kg steel sheet). The derivation of the per unit impact values is discussed below.

Inputs¹	Density (ρ_{metal})	CED²	GWP	Human health
Electricity	N/A	MJ/kWh	kgCO₂e/kWh	DALY/kWh
Medium voltage ($i_{\text{electricity}}$)	N/A	13	0.7	4.7E-07
Sheet Metal (i_{sheet})	kg/m³	MJ/kg	kgCO₂e/kg	DALY/kg
Low carbon steel sheet (r=0%)	7,850	31.3	2.5	3.2E-06
Generic alum. sheet (r=24.2%)	2,700	180.3	15.5	2.1E-05
Aluminum sheet (AA7075) r=24.2%	2,810	175.5	14.8	2.1E-05
Aluminum sheet (AA6014) r=24.2%	2,700	181.9	15.5	2.1E-05
Aluminum sheet (SP5083) r=24.2%	2,660	202.3	16.9	2.4E-05
Galvanization (for steel sheets)	Thickness	MJ/m² sheet	kgCO₂e/m² sheet	DALY/m² sheet
Galvanizing (i_{galv}) ³	20-45 μm thick	82.1	5.3	1.8E-05
Lubricants	kg/m³	MJ/kg	kgCO₂e/kg	DALY/kg
Lubricating oil	845	84.1	4.0	1.4E-06
Graphite	959	59.1	4.7	6.7E-07
As Cast Die Material ($i_{\text{die-making}}$)	kg/m³	MJ/kg	kgCO₂e/kg	DALY/kg
Casting iron (r=65.7%)	7,150	30.9	2.0	3.1E-06

Casting zinc (r=97.5%)	6,920	16.4	1.0	9.7E-07
Bulk Alum: AA7075 (r=24.2%)	2,700	164.9	14.2	2.0E-05
Machining Listed Material (i_{die-machining})	kg/m³	MJ/kg_{removed}	kgCO₂e/ kg_{removed}	DALY/ kg_{removed}
Cast iron	7,150	4.4	0.2	1.8E-07
Cast zinc	6,920	10.4	0.6	3.5E-07
Bulk aluminum (AA7075)	2,700	6.9	0.4	3.3E-07

1. “r” refers to the recycled content of the material.
2. A CED value for electricity (13 MJ/kWh) corresponds to a conversion efficiency of 28%.
3. Impacts account for galvanizing on both sides of the sheet.

Table 3: Intrinsic model input environmental impacts (r: recycled content)

The environmental impacts of producing electricity were modeled using ecoinvent 3.1 medium voltage database entries for the USA averaged by production volume. Ecoinvent 3.1 contains database entries for bulk low carbon (mild) steel (“Steel, unalloyed {GLO} | market for | Alloc Rec, U”) and the hot and cold rolling processes that create steel sheet: “Hot rolling, steel {GLO}...” and “Sheet rolling, steel {GLO}...” respectively. Ecoinvent also includes a generic bulk aluminum wrought alloy (“Aluminium, wrought alloy {GLO}...”) and the rolling process to create aluminum sheet (“Sheet rolling, aluminium {GLO}...”). These entries (excluding the highly variable values of transportation to the customer) were used to create the generic steel and aluminum sheet entries. Table 3 includes both of these values as well as the calculated impacts for the specific alloys (AA6014, AA7075 and SP5083) used in the case studies. The impacts of these alloys were modeled by modifying the generic aluminum sheet entry using the alloy compositions listed in the Aluminum Association’s ‘Teal Sheets’ (The Aluminum Association, 2015). The impacts of these alloys were modeled using ecoinvent 3.1 for most alloying elements, and the Idemat database for vanadium. Superplastic materials (SP5083) require extra sheet rolling in order to achieve a fine grain size. Per Rossie (2015), this additional processing energy was modeled as the energy of five additional rolling passes at 0.12 kWh/pass (Milford et al., 2011), with a small 5% increase in yield loss.

Sheet metal is a globally traded commodity. Regional variations in recycled content exist, but all affect the global price. Thus, ecoinvent 3.1's global average recycled content values for sheet metal were used in this paper's analysis. For the case of steel sheet, the lack of any electric furnace (melted scrap) content in the ecoinvent 3.1 entry appears to be an arbitrary artifact of the modeling process: there is no discussion in the ecoinvent documentation, and ecoinvent's final impact values for steel sheet are within the range of other sources that model the recycled content between 20 and 42% (Hammond and Jones, 2011; Milford et al., 2011; Ashby, 2012). As such, the ecoinvent 3.1 entry was not updated.

Ecoinvent 3.1 contains an entry for galvanization of steel sheets and that was used, unchanged, in this analysis ("Zinc coat, coils {GLO}..."). The forming process requires a small amount of lubricant, which then must be disposed of afterwards. The lubricant used in most of the processes is a type of oil or grease, modeled as the sum of ecoinvent's "Lubricating oil {GLO}..." and "Waste mineral oil {GLO}..." entries with transportation to the customer removed. These entries assume a lubricant derived from diesel. In the case of aluminum SPF, a graphite lubricant is used. Rossie (2015) modeled this lubricant based on the material data safety sheets (MSDSs) for Formkote T-50-66 lubricants with 10% graphite content suspended in a mixture of toluene, xylene, and ethyl benzene. Table 3 includes the impacts calculated by Rossie (2015) .

Previous researchers have determined the impacts of casting and machining cast iron (Rossie, 2015), casting and machining zinc (Cooper et al., 2016), and making and machining bulk AA7075 aluminum (Rossie, 2015). Table 3 includes their calculated impact values.

3.2 Case study results

This results section first presents the electrical power measurements on each case study. The electricity requirements inform the modeling of each case study's environmental impacts, presented in the second sub-section.

3.2.1 Electrical energy requirements

Figure 4 shows the active (real) power and cumulative energy during forming of multiple case study parts: seven drawn parts, eight stretch formed parts, six FCF parts, five SPF parts, and three ISF parts in addition to an ISF cycle in which the tool path was run but with no blank installed. Figure 5 presents the power draw for a single forming cycle for each process.

Figure 4: Electrical power and energy requirements for making multiple case study parts: 7 drawn truck hoods, 8 stretch formed ‘U’ parts, 6 FCF rectangular and semi-circular parts, 5 SPF semi-truck bumpers, and 4 ISF truncated cones (1 cycle without a blank present). PF = power factor

Figure 5: Electrical power requirements and average power factor for making a single case study part using each process. PF = power factor

Electrical-mechanical-hydraulic systems: drawing, stretch forming, and FCF

In the hydraulic drawing, stretch forming, and FCF presses, electricity is used primarily to drive fixed speed induction motors that power pumps used to pressurize oil. This pressurized oil provides the forming force either via rams and dies in the case of drawing and stretch forming, or an expanding rubber bladder in the case of FCF. Whenever the machine is on, regardless of whether in use or idling, the fixed speed motors continuously circulate hydraulic fluid, meaning that these processes require relatively high baseload power.

For drawing, most of the cycle time is due to manual blank and part handling. Figure 4a shows a power spike at over 200 kW corresponding to the inrush current when the press is turned on. Baseload power is then 19 kW. As shown in Figure 5a, as the top die descends the power draw grows to 32 kW. The power consumption increases rapidly when the female die makes contact with the ring (blank holder) and starts to compress the draw cushion. The blank is formed over the post as the die descends approximately 150 mm. The power spike at over 120 kW corresponds to contact between the die and rigid post. The power factor is only 0.5 during most of the forming process, but reaches 0.9 as the die contacts the post and applies the full forming load (750 short tons).

In the case of stretch forming, all press movements are controlled manually by an operator. The operators took an average of 3 minutes to remove the large formed part and add a new blank. The baseload power is 53 kW, which is much higher than drawing. The high power draw is likely due to stretch forming relying on tensile deformation, which demands high forming forces and thus powerful hydraulics; in fact, the stretch forming machine has the highest cumulative motor capacity of any machine in the case studies. To make a part the blank is inserted into the grippers, the clamping force is engaged, and the die table is raised until it is just in

contact with the blank. These movements require around 70 kW and take around 1.1 minutes (see Figure 5b). Next, forming begins and the process is at maximum power consumption as the material is stretched by continuing to raise the die table. The die table is then locked into position for 1-2 minutes. During this time, the operators are checking the material to ensure that it is properly formed. The grippers are then opened and the die table lowered.

For FCF, power consumption varied between 50-307 kW. For this process, the operator only sets the peak forming pressure and the press's computer controls ramping speed. The forming time and power profile is very consistent between passes compared to either drawing or stretch forming (see Figure 4). As shown in Figure 5c, during a cycle the forming tray is first jogged into place. Second, the fluid behind the bladder is pumped to the maximum programmed pressure. Lastly, the fluid is pumped out while the tray is moved out of the forming area. The whole forming process takes on average 1.6 minutes. Blank set-up and part removal generally takes longer than the other processes because FCF is often used to form many small parts at once and blanks are often held in place with several clips. During the case study only two parts were formed.

Other mechanisms: SPF and ISF

In the SPF press and ISF machine, electricity is not primarily used for hydraulic systems. In SPF, over 85% of the power is used to maintain the press at the high forming temperature using resistance heating. In ISF, the power is split between the motors used to directly drive the indenters along the forming tool path and the hydraulic blank holding system.

Figure 4d shows the power draw for forming five semi-truck bumpers using SPF. The power shown accounts for all sub-systems other than the air compressor, which provides the forming pressure (consuming approximately 3.9 kWh per part). Table 4 shows the electrical energy breakdown per part.

Contributor	Energy (kWh)	Contribution
Heating	94.5	86.9%
Computer & cooling	0.5	0.4%
Hydraulics – Low pressure	2.2	2.0%
Hydraulics – High pressure	7.7	7.1%
Forming pressure (air compressor)	3.9	3.6%
Total	108.8	100%

Table 4: Electrical energy breakdown per part for SPF case study

As shown in Figure 4d and 5d, a peak in power is seen at the start of each new SPF cycle, corresponding to the press doors being opened and a new, cold blank being inserted. The door is then closed and the blank heats up to the forming temperature. Over the first 8 minutes the pressure chamber and lower die are brought together, but no significant force is applied. The clamping force is then applied and increases over 10 minutes until the blank is rigidly clamped around its periphery. The pressurized air is then applied. During the next 21 minutes the air pressure and clamping force continue to increase as the blank is forced against the die. Overall cycle time including blank loading and part unloading is 46 minutes on average. The average power factor (excluding the air compressors) during the forming cycle is 0.98. The power factor is high because the energy requirements are dominated by resistive heating.

In order to examine the power characteristics of ISF, four different sets of forming parameters are used to incrementally form truncated cones. In all cases the choice of forming parameters has a minimal impact on the power draw, even when no sheet is present and the tools traverse the tool path in air. Thus, electricity requirements are determined by the forming time, which is determined by the size of the final part, the tool speed, and the vertical step size. Figure 5e shows that the baseload power of ISF is very low compared to the other processes. The 0.7 kW corresponds to running the computer, controller, and lighting. However, after set-up, an additional 1.1 kW of power is required to run the hydraulic blank holding

mechanism. The cooling system for the controller also intermittently increases the power requirements by an additional 1 kW. The magnified image in Figure 5e shows that the power draw rises and falls in sync with the vertical rise and fall of the forming tools (the plane of the blank surface is vertical in this ISF machine). An average power factor of 0.31 implies that the motors used to move the indenters are over-sized for this application. It should be noted that as an emerging technology there has been less time and emphasis so far on design optimization of ISF than on the more traditional processes.

Summary of results

Table 5 summarizes the average cycle times and electricity consumption measured in the case studies. The high baseload power requirements of many of the processes means that even between forming cycles significant electricity is consumed. These energy requirements are attributed to the final parts and labeled as “Part set-up” in Table 5. For stretch forming and SPF, significant electrical energy must also be used during “Batch Set - Up.” In the case of stretch forming, the small batch sizes of the aerospace industry (often less than 20 parts) means that the machine is left on while the die is swapped out and adjustments are made to the die table and gripper. The entire batch set-up takes about 30 minutes. In the case of aluminum SPF, the batch set-up electricity is used to heat the die-set from room to forming temperature, requiring ten hours and 1,560 kWh of electricity in the case study. The energy requirements of “Batch Set-Up” are attributed to individual parts by amortizing them over the number of parts produced in that batch before the next die-set changeover.

Case study	Average cycle time (mins)	Average forming time (mins)	Average cycle power (kW)	Baseload power (kW)	Batch set-up energy (kWh)	Part set-up energy (kWh)	Forming energy (kWh)	Marginal energy of forming (η)	Energy per part (kWh)
Drawing	2.8	0.2	26	19	0	1	0.2	11%	1.2
Stretch forming	9.8	6.8	99	53	3.5	2.6	10.1	25%	16.2
FCF	6.5	1.6	58	52	0	4.2	2.1	11%	6.3
SPF	46	41	165	124**	17.4	10.3	98.5	11%	126.2

ISF*	135	110	3.2	0.7	0	0.7	6.4	72%	7.1
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- *Corresponds to part 1 in Figure 4e
- **Corresponds to heating energy and computer power

Table 5: Summary of electrical energy and power results from the case studies

The ‘marginal energy of forming’ (η) is included in the table and defined in equation 1. It is equal to the energy the machine uses to form a part above what it would consume in idling mode, as a fraction of the total cycle energy.

$$\eta = \frac{\text{Forming energy} - (\text{Baseload} \times \text{Forming time})}{\text{Total energy per part}} \quad (1)$$

FCF is the only process in which multiple parts can be made simultaneously. In the case study, only two small dies (projected horizontal surface areas of 0.31 m² and 0.065 m² for the rectangular and semi-circular parts respectively) were present in the forming tray. This was an artifact of the case study only; typically, the tray (with an area of 4.36 m²) would be around 70% full (3.05 m²). A realistic tray-filling rate of 4.7 min/m² was calculated based on the case study observation of a single operator and a scenario more in keeping with industrial application (with four operators filling the tray with sheet metal blanks). Given that the machine’s baseload power draw is 52 kW, this means that the set-up energy is 4 kWh/m² die surface area. Similarly, the forming energy can be attributed per unit area of die, equal to 0.7 kWh/m² die surface area, giving a total energy per part of 4.7 kWh/m² die surface area. This energy intensity was multiplied by the case study dies’ surface areas in order to model the electrical energy per case study part.

3.2.2 Cradle-to-gate energy requirements and environmental impacts

The average electrical energy needed at the forming machine was modeled in SimaPro along with the other case study inputs (die-set, sheet metal,

and lubricants). Each case study input was normalized to the production of a single part. It was found that lubricant accounted for less than 1% of total impacts regardless of the forming process case study or impact metric considered. Thus, in the results, the impacts of using lubricants are included in the impacts for sheet metal and not assigned their own values.

Figure 6 shows the CED and environmental impacts (GWP and DALYs) for the stretch forming case study. Figure 6a shows that the CED per part is dominated by the production of the sheet metal and that much of the sheet used in the process is ultimately scrapped (see the solid shaded portion of the 'sheet metal' bar). The dominance of sheet metal grows even further when the GWP or human health impacts are considered (Figure 6b and 6c respectively) as a result of the relatively high carbon intensity of the electricity used to make aluminum and also due to the toxic substances produced as part of metal ore mining and refining. Aluminum production has seen a rapid shift to production in China, where 90% of the electricity used to make aluminum comes from coal, resulting in a global value of over 50% coal (International Aluminum Institute, 2013). An example of a toxic substance is red mud produced in the Bayer process for refining aluminum ore.

Figure 6 is representative of all the case studies in terms of how the significance of the inputs changes depending on the impact considered. As such, GWP and DALY values are not shown for the other case studies.

Figure 6: Environmental impacts from the stretch forming case study (750 parts/die) (8 parts/batch). The solid shaded portion of the ‘sheet metal’ bar represents scrapped material.

Figure 7 shows the cumulative energy demand for the drawing, FCF, SPF, and ISF case studies. Across all processes the sheet metal is the dominant contributor to the CED. Significant quantities of purchased sheet metal do not make it into the final part and are scrapped in the blanking and trimming processes. In the ISF case study only 25% of the purchased sheet made it into the final truncated cone. In the authors' experiences, such a low material yield is typical in ISF; however, as the technology matures there is potential to improve matching between the frame size and shape and the desired part size and shape. In the FCF case studies, flanged parts were formed over male dies, and there were no trimming losses. The blanks used in FCF, although irregular shapes, were cut from flat sheet metal stock. Nesting software that tessellates blanks was used to reduce waste in the blanking process. Overall, a blanking yield of 85% was achieved in the case studies.

Figure 7: Environmental impacts from other case studies: drawing, FCF, SPF, and ISF

The impacts of making the die-set have, in each case study, been divided by the total number of parts made on the die over its lifespan. The smallest production number over a die lifespan was 250 parts. The impacts of die-making, although not dominant in the case studies, would be more significant for smaller numbers of parts.

The press electricity is negligible for the case studies of drawing and FCF. In these cases the electrical energy is dominated by the part set-up energy. The heating requirements in SPF make the press electricity a significant contributor to overall CED (around 22%), and the impacts of electricity are equivalent to the impacts of sheet metal for ISF. It should be noted that the ISF case study uses steel sheet, the production of which requires only around 20% of the primary energy needed to make aluminum sheet.

4 Global models of process impacts

The results from the case studies are specific to the parts considered, ranging in size from 0.15 kg to 15.5 kg. In this section, the case study results are used to help develop generalized global models that allow energy use and environmental impacts to be estimated based on limited information about the final part. The global models are then used to examine each process's energy (CED) characteristics for varying numbers of parts produced over the die lifespan, and the potential for ISF to save energy when used instead of drawing.

4.1 Deriving global models

The global models constructed in this section allow environmental impacts to be estimated based on as little information as the process used, the number of parts produced over the die-set lifespan (N), final part material, surface area (X square meters, corresponding to one side), thickness (T meters), and depth (h meters).

Equation 2 presents a simple representation of the impacts per part. The impacts of the die are amortized over the total number of parts made using that tool (N). As described in Section 3.2.2, lubricants have negligible impacts and can be ignored in the predictive model.

$$I_{\text{per part}} = I_{\text{sheet}} + I_{\text{press-electricity}} + \frac{I_{\text{die}}}{N} \quad (2)$$

The impacts of the sheet metal (I_{sheet}), press electricity ($I_{\text{press-electricity}}$), and die (I_{die}) can be expressed as equations 3-5, where α is the overall material yield from stock sheet to final part (ratio of mass of the part to mass of the stock sheet); ρ_{metal} is the density of the sheet metal (in kg/m³); $W_{\text{press-electricity}}$ is the metered electrical energy needed to form a part (in kWh);

M_{die} is the mass of the cast die (in kg); and $M_{\text{machined-away}}$ is the mass of the cast die that is machined away to produce the final die shape (in kg).

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

$$I_{\text{press-electricity}} = i_{\text{electricity}} W_{\text{press-electricity}} \quad (4)$$

$$I_{\text{die}} = i_{\text{die-making}} M_{\text{die}} + i_{\text{die-machining}} M_{\text{machined-away}} \quad (5)$$

Practitioners are free to fill in their own values where available.

Otherwise, the intrinsic impacts and densities of the inputs (i_{metal} , i_{galv} , ρ_{metal} , $i_{\text{electricity}}$, $i_{\text{die-making}}$ and $i_{\text{die-machining}}$) are given in Table 3. Table 6 presents representative values for the other variables in equations 3-5 (α , $W_{\text{press-electricity}}$, M_{die} and $M_{\text{machined-away}}$) as functions of the process and the final part shape. The precise values depend on many details of the part shape (e.g., whether the shape has holes or deep “features”) and process machine architecture. Such detail is neglected in favor of creating a simple model with uncertainty assigned to the variables (see Table 6). The following sub-sections describe the derivations of the values presented in Table 6.

	Drawing (hydraulic press)	Stretch forming ¹	Fluid cell forming	Superplastic forming ¹	Incremental sheet forming ²	Uncer- tainty ₅
Press electricity ($W_{\text{press-electricity}}$) [kWh/part]	1.2	$12.7 + \left(\uparrow \frac{N}{B}\right) \times \left(\frac{27.5}{N}\right)$	$4.7 \cdot \frac{X}{a_{\text{trim}}}$	$(36300T) + \left(\uparrow \frac{N}{B}\right) \left(\frac{474 \times X}{N \times a_{\text{trim}}}\right)$	$0.7 + 10.3 \frac{h \cdot \sqrt{X}}{v \cdot s}$	$\pm 50\%$
Cycle time (hours)	$\frac{2.8}{60} = 0.05$	$\frac{9.8}{60} = 0.16$	$\frac{6.5}{60} = 0.11$	$\frac{15 \cdot T}{60} = 0.25T$	$\frac{25}{60} + 3.03 \frac{h \cdot \sqrt{X}}{v \cdot s}$	$\pm 25\%$
Die material ³	Zinc	Zinc	Zinc	Iron	N/A	N/A
Die mass (M_{die}) [kgs]	$4590 \cdot \frac{X}{a_{\text{trim}}}$	$1695 \cdot \frac{X}{a_{\text{trim}}}$	$2190 \cdot \frac{X}{a_{\text{trim}}}$	$1560 \cdot \frac{X}{a_{\text{trim}}}$	0	See Note 4 below
Die mass machined ($M_{\text{machined-away}}$) [kgs]	$0.15M_{\text{die}}$	$0.1M_{\text{die}}$	$0.1M_{\text{die}}$	$0.1M_{\text{die}}$	0	$\pm 25\%$
Overall material yield (α)	0.52	$\frac{0.9X}{X + 0.86\sqrt{X}}$	0.64	0.36	$\frac{0.9X}{X - \text{frame area}}$	$\pm 35\%$ app- plied to I_{sheet}
Blanking yield (α_{blank})	0.8	0.9	0.8	0.9	0.9	N/A
Trimming yield (α_{trim})	0.65	$\frac{X}{X + 0.86\sqrt{X}}$	0.8	0.4	$\frac{X}{X - \text{frame area}}$	N/A

1. B is the number of parts produced during that batch. $\uparrow$ indicates rounding up the fraction, $\uparrow \left(\frac{N}{B}\right)$ up to the nearest integer. For SPF, B cannot be greater 100.
2. In the case of ISF, $\uparrow$ indicates rounding up to the nearest ISF square frame size area. h is the part depth (in meters), v is the tool speed (in meters per hour), and s is the tool vertical step size (in meters, perpendicular to the plane of the blank). Note that the 10.3 factor in press electricity equals the product of the 3.4 kW average power draw and the 3.03 constant of proportionality from the cycle time calculation.
3. The choice of labeled die materials assumes that the dies are cast and then machined. However, dies for small parts are sometimes machined from stock metal blocks. Such dies must be steel for SPF given the high temperatures of the process, but are likely to be either aluminum or steel for the other processes.
4. Drawing error: $\pm 45\%$; Stretch forming error: $\pm 90\%$; FCF error: $\pm 90\%$; SPF error: $\pm 90\%$; ISF error: 0%.
5. The uncertainties are modeled as uniform distributions.

Table 6: Forming characteristics for different processes used in predictive global models

4.1.1 Electrical energy requirements ($W_{\text{press-electricity}}$)

The electrical energy needed to form a sheet metal part depends on the forming time and power requirements. These factors have already been determined for the case study parts. In order to produce global models it is necessary to examine how these factors change when making different

parts. The global models assume use of equipment of a similar size and design as the case study presses. Rossie (2015) provides guidance on how the electrical energy requirements may vary when using different equipment types and sizes, finding that the stretch forming, FCF, and SPF presses used in this paper's case studies are typical of those used in the aerospace industry.

For drawing, the dynamics of the press (in mass production) or the part set-up time (in low volume production) typically determines the production rate. Cooper et al. (2016) find that for a given hydraulic press the electrical energy consumption is independent of the forming force required, indicating that the electrical energy requirements are independent of the final part geometry. The electrical energy used to operate the press in the drawing case study (1.2 kWh/part) can therefore be taken as representative of the energy required to make any part on that hydraulic press.

In the stretch forming case study, the forming energy was 10.1 kWh. The marginal energy of forming (see Table 5) was 25%, indicating that the forming power is relatively independent of the part being made.

Discussions with an aerospace manufacturer indicate that stretch forming times are reasonably independent of differences to the part being formed because the die table always moves a similar distance to engage the sheet, part depths are often similar, and the maximum forming speed is limited to avoid the appearance of Lüders bands. Part set-up (2.6 kWh) is also reasonably part independent because while blanks vary in size, blank shape is constant and the clamping process is always similar. Batch set-up (27.5 kWh) is included in the stretch forming equation because in aerospace production batch sizes are very small. At the case study site, batches typically ranged from 6 – 30 parts, with an average of 10. This means both that workers do not turn off the machine during die changeovers (as they happen so frequently) and that the energy of batch

set-up is amortized over few parts. Batch set-up can vary from 15 to 40 minutes, with 30 minutes being typical.

For FCF, forming time is fixed at around 1.5 – 2.0 minutes (the case study was 1.6 minutes). The forming pressure is adjusted according to the sheet material and part shape. However, in the case study the marginal energy of forming (see Table 5) was only 11%; forming time is always short and close to the case study value. Thus, changes in forming pressure are insignificant to overall electricity demand, and the electrical energy can be modeled as 4.7 kWh per square meter die area (as described in Section 3.2.1). In Table 6 it is assumed that the blank area is roughly equal to the die surface area (4.7 kWh per square meter of blank).

The average power draw during SPF is relatively unaffected by whether or not forming is taking place; the marginal energy of forming is only 11% (see Table 5) and corresponds to work by the hydraulic pumps and air compressor. Part set-up time is a function of part unwieldiness and varies from 3-10 minutes. Forming time is a function of the thickness of the blank and the tightest radii and ranges from 10-60 minutes. The minimum feature radius in SPF is 3 times the thickness, which corresponds to cycle times approaching the top of the 10 – 60 minute range. The case study part's long forming time of 41 minutes was due to its 3 mm thickness. In the global analysis it is assumed that the cycle time is directly proportional to the thickness of the part, resulting in an energy requirement of 36,300 kWh per meter of blank thickness (36.3 kWh per millimeter). A more complex analysis could also consider the feature radius.

Significant batch set-up energy is required to heat the die-set from room to forming temperature (an increase of approximately 475°C). In the case study, the minimum theoretical heating energy requirement (specific heat coefficient for cast iron, 1.28×10^{-4} kWh/kg°C) corresponded to only 18% of the total batch set-up heating energy (1,566 kWh). Using this scaling

factor, the heating requirements for any sized die can be estimated as shown in equations 6-8.

$$\text{Batch set-up energy}_{\text{SPF}}(\text{kWh}) = \frac{475 \cdot (1.28 \cdot 10^{-4})}{0.18} \cdot (M_{\text{die}} - M_{\text{machined-away}}) \quad (6)$$

$$\text{Batch set-up energy}_{\text{SPF}}(\text{kWh}) = \frac{475 \cdot (1.28 \cdot 10^{-4})}{0.18} \cdot 0.9 \cdot 1560 \cdot \frac{X}{a_{\text{trim}}} \quad (7)$$

$$\text{Batch set-up energy}_{\text{SPF}}(\text{kWh}) = 474 \cdot \frac{X}{a_{\text{trim}}} \quad (8)$$

The maximum batch size (B_{max}) in SPF is one hundred parts. At this point, the die must be cooled and the build-up of graphite lubricant cleaned before the die can be heated up again and production continued.

In the ISF case study, blank set-up and part retrieval took a total of 25 minutes with an average power draw of 1.7 kW (0.7 kWh). The set-up and retrieval time is mainly accounted for by the machine jogging into place (zeroing axes, etc.) and is unlikely to vary significantly between parts. Thus, 0.7 kWh is used in the global model for part set-up. The case study also demonstrated that the average power draw during forming in ISF is unaffected by changes in the forming mode (e.g., SSIF versus DSIF) or part material; therefore, the case study power value of 3.4 kW can be used for any part.

The tool speed (v , in meters per hour) and the total length of the forming path (l , in meters) determine the ISF forming time. It is postulated that, for a given aspect ratio, the average length of a tool path orbital (once around a part) approximately scales with the square root of the part area. The depth of the part (h , in meters) and the tool vertical step size (s , in meters, perpendicular to the plane of the blank) determine the number of orbitals (h/s). Subsequently, it is postulated that the forming time is given by equation 10.

$$\text{ISF forming time (hours)} \approx k \times \left(\frac{h \times \sqrt{X}}{s \times v} \right) \quad (10)$$

The dimensionless constant of proportionality (k) depends on the aspect ratio and surface topology of the part being formed, but a representative value was estimated by forming a ‘realistic’ car part on the ISF machine: a 40% scale version of a sports car hood with a surface area of 0.45 m², depth of 0.07 m, tool speed of 300 m/hour, and a tool vertical step size of 0.0001 m (0.1 mm). The total forming time was 4.75 hours (285 minutes). The resulting constant of proportionality relating to equation 10 is therefore $k = 3.03$. In order to ensure that this model is reasonably representative across different parts, data on a range of incrementally formed parts were extracted from the literature. The reported forming times were then compared to the times calculated using Equation 10. Figure 8 shows that equation 10 provides a reliable estimate of ISF forming times.

Figure 8: Predicted ISF forming times with $\pm 25\%$ error bars (using equation 10) and actual forming times found in the literature

An uncertainty of $\pm 50\%$ is assumed in the predictions of press electrical energy requirements. This uncertainty is equal to double both the ‘marginal energy of forming’ for stretch forming (see Table 5) and the uncertainty in our method of predicting ISF forming times (see Figure 8). An uncertainty of $\pm 50\%$ is therefore deemed conservative.

4.1.2 Die-set requirements (M_{die} and $M_{\text{machined-away}}$)

The car and aerospace manufacturers provided a set of part and die-set information. This data was compiled in order to produce Figure 9.

Figure 9: Blank area and die volumes for different processes. Blue data points indicate dies made by casting and then machining of a metal. Red data points indicate dies made by machining from a bulk metal. Data supplied by car and aerospace manufacturers

In the case studies, the dies used in drawing, stretch forming, and SPF were made by casting either zinc or iron and then machining to produce smooth sheet contacting surfaces. Note that the SPF dies cannot be made from cheaper zinc because of the high forming temperatures. The small die-sets used in the FCF case studies were instead made by machining a

bulk aluminum block. Aluminum is a cheaper option for very small die-sets and is also sometimes used for the other processes; however, larger FCF dies (on the order of the case study parts for the other processes) are also made by casting and then machining zinc. Figure 9 indicates that as blank sizes increase above 0.75 m^2 , corresponding to a die volume of around 0.3 m^3 , all forming processes switch to using cast and machined metal dies.

Figure 9 is used to predict the mass of a die for a given blank size by applying a linear line of best fit passing through the origin to the data for each process. These equations have been re-written in terms of mass using the density of zinc and iron (therefore assuming cast and machined die-sets) and are presented in Table 6. An uncertainty is assigned to each of these calculations (shown in Note 4 of Table 6) depending on the quality of data for the process and likely divergence from linearity due to parameters such as part shape.

The dies are machined to produce smooth sheet contacting surfaces. Cooper et al. (2016) find that the mass machined for zinc drawing dies corresponds to 15% of the cast mass. For the other processes there is no need to match two die halves; therefore, it is assumed that less material (equivalent to 10% of the cast mass) is machined. In the case studies, 7% of the cast mass is machined for SPF and 10% of the cast mass is machined for stretch forming.

4.1.3 Material yield (α): Sheet metal requirements for different parts and processes

The quantity of purchased sheet metal stock required to form a part depends on both part geometry and the forming process selected. Material is scrapped from the stock as part of the blanking (cutting the flat shape for subsequent forming) and trimming (cutting any holes and removing the excess material on the periphery of the formed part) processes.

The sheet metal stock is constant width rectangular sheet or coil that is generally available in only a small number of standard widths. In this analysis, unless otherwise specified below, it is assumed that rectangular blanks are cut from stock with a material yield of 90%; however, because irregular shapes are more difficult to tessellate, non-rectangular blanks are produced with a material yield of 80%.

The trimming yield depends on both the process and final part geometry. In order to keep the equations simple, in this analysis trimming yields are modeled only as a function of the process, and in the case of stretch forming and ISF, also the final part surface area. It is recognized that this simplification introduces errors into the analysis.

The drawing trimming yield is estimated as the average yield (65%) found in an extensive study on drawing of car parts by Omar (2011). Similarly, the trimming yield for the steel car door case study found in Milford et al. (2011) is 68%.

For stretch forming, the trimming yield typically increases for larger parts because a constant width of sheet (around 17 inches or 0.43 m) on two opposing sides of the sheet, corresponding to the metal clamped in the grippers and extending from the grippers towards the forming die, must be trimmed. The equation presented for the stretch forming trimming yield in Table 6 assumes a square blank (for the sake of simplicity) and calculates the yield as a function of the final part surface area ($X \text{ m}^2$). As a sense check, this method predicts a trimming yield for the stretch forming case study part of 58%. This estimated trimming yield compares to the real value of 63%. It should be noted that in some cases there is also excess sheet (around 5 inches per side) in the direction perpendicular to the plane between the grippers. Although not modeled in this analysis, this excess material would further decrease the trimming yield.

As discussed in the introduction, FCF can be used to produce a variety of part shapes. Some are drawn into a die cavity; the periphery of the part

will then have to be trimmed to produce the final shape. Some are wrapped around a male die to produce, for example, flanges, with no post-forming trimming necessary. In Table 6, a generic in-between value for the trimming yield (80%) is chosen as representative.

In the SPF case study, a trimming yield of 58% was found. The manufacturer indicated that this trimming yield is a typical value but that yield can be as low as 20%. Discussions with other manufacturers suggested an average trimming yield of 40% in titanium SPF. In the absence of other data, and given that 40% is roughly mid-way between the other confirmed values, the global analysis presented in Table 6 uses a trimming yield of 40%.

For ISF, the trimming yield is determined by the size of the frame that holds the rectangular blank. The denominator of the term in Table 6 ($X \uparrow$ frame area) is therefore equal to the final part surface area rounded up to the area of the closest square frame size. This calculation assumes a square blank for the sake of simplicity. The ISF machine uses square frames of the following sizes: 0.25, 1, and 2.25 m². These values were used to predict yields when calculating the CED impacts presented in Figure 10 and Figure 11.

4.2 Producing different numbers of parts over the die-set lifespan

The models presented in Section 4.1 can be used to examine the processes' electrical energy and CED characteristics while producing different numbers of parts. In this sub-section, forming a generic aluminum part is modeled. The part has a surface area (one-side) of 1.5 m² and a thickness of 0.0015 m (1.5 mm). These dimensions lie in the middle of the range of case study parts (see Table 1). Further, it was also assumed that the tool speed is as high as possible on the ISF machine (300 m/hour), that the

forming depth is 0.07 m (70 mm, the same as the car hood described in Section 4.1.1), and that the ISF step size is 0.0001 m (0.1 mm).

Figure 10 shows the predicted CED for producing the aluminum part using each process. The error bars in Figure 10 correspond to one standard deviation away from the mean. The error bars were constructed from the uniform distribution uncertainties presented in Table 6 and by modeling perfect correlation between blank size and die size in order to calculate covariance.

Figure 10: The effect of production number over the die lifespan (N) on per part CED. Generic aluminum part modeled: 1.5 m², 1.5 mm thick. Forming depth (for ISF calculation): 70 mm. In the case of stretch forming, $B=N$. In the case of SPF, for $N<100$, $B=N$, otherwise $B=100$

Several trends can be established by examining Figure 10, despite large uncertainties in the predictions. When only a few parts are required (less than 30), ISF can potentially save significant amounts of energy compared to the other processes. Drawing is a very energy intensive process when only a few parts are required because of the relatively large die-set needed. As the number of parts increases, the die-set impacts are quickly amortized and per part impacts have reduced to the level of ISF by 1,000

parts. For larger production volumes, zinc dies would likely be replaced by iron or steel die-sets. Superplastic forming is, like stamping, energy intensive when only a few parts are required because of the need to heat the iron die from room to forming temperature. As the number of parts required approaches 1,000, the energy curve for SPF plateaus due to the high per part forming electricity requirements and the energy intensity of superplastic sheet metal alloy production. FCF and stretch forming display similar trends as the number of parts increases. FCF becomes less energy intensive than ISF at around 170 parts.

Figure 11 shows the CED of the different inputs (dies, sheet metal, and electricity) for a production number over the die lifespan of 100 parts. It can be seen that electricity is a negligible contributor to the overall impacts in drawing; however, electricity is significant for the cases of SPF and ISF. As with the case studies examined in Section 3.2.2, the sheet metal dominates overall energy requirements.

Figure 11: CED impacts for a production number over the die lifespan of 100 parts

Figure 12 shows the metered electrical energy consumption for the same batch size and production number over the die lifespan as Figure 11.

Nearly all of the electrical energy needed in ISF is used during forming, whereas FCF, SPF, and drawing are dominated by either batch set-up or blank set-up.

Figure 12: Metered electricity requirements for a production number over the die lifespan of 100 parts

4.3 Using incremental forming to save energy

Several authors have already highlighted the opportunity to save energy by using (dieless) ISF instead of drawing (Ingarao et al., 2012; Dittrich et al., 2012). In order to examine this opportunity, the models presented in Section 4.1 were used to calculate the likely per part CED changes caused by a switch from using drawing to using ISF when making 1.5 mm thick aluminum parts. The parameters explored include the number of identical parts produced (production number over the die lifespan), part size, forming depth, and relative material yield. Using 25-node “flags,” Figure 13 shows the results of this analysis. The relative vertical position of a node represents the part size surface area as shown in Figure 13a. The horizontal position of a node represents the material yield of ISF relative to drawing; the drawing yield is fixed at 52% (80% blanking yield

multiplied by 65% trimming yield). For example, the middle horizontal nodes at “0%” correspond to an ISF yield equal to drawing’s 52%; “+15%” corresponds to an ISF yield of 67%, and so on. The absolute vertical position of each node in Figure 13b represents per part CED savings (positive values) or losses (negative values) using ISF.

(a) Each node of a flag represents two parameters: part size and ISF material yield compared to drawing

(b) CED savings (per part) when using ISF instead of drawing

Figure 13: Per part CED energy savings caused by a switch from drawing to ISF

In order to produce the data shown in Figure 13, the ISF tool speed was fixed at 300 m/hour and the vertical step size at 0.0001 m (0.1 mm). Changes in the step size, although not shown in Figure 13, would mirror changes in the forming depth.

Figure 13 shows that as the production number over the die lifespan increases, the energy (CED) savings from using ISF instead of drawing decreases. This is because the high upfront energy investment from making the drawing die-set is amortized over a greater number of parts. The energy (CED) savings from using ISF instead of drawing also decreases as the depth of the formed part increases; the electricity needed to operate the ISF machine increases for deeper parts because a greater number of tool path orbitals is needed for a given step size. Figure 13 also shows that as the part surface area increases (corresponding to higher nodes on the flags), the energy (CED) savings from using ISF instead of drawing increases. This is because the size of the drawing die (and therefore die-set CED) is scaling with the part surface area (see Figure 9 and the “Die mass” row of Table 6), whereas the ISF forming time (and therefore electricity CED) is scaling only with the square root of the part surface area (see equation 10). Figure 13 shows, as one would expect, that the higher the ISF material yield compared to drawing (corresponding to nodes on the right hand side of the flags), the greater the energy (CED) savings from using ISF instead of drawing. Collectively, the trends displayed in Figure 13 show that when only ten parts are being made ISF always offers low energy (CED) per part compared to drawing. For larger production numbers, the importance of material yield grows. At fifty parts, it is possible for ISF to require greater energy (CED) per part than drawing if the material yield is 30% lower than that of drawing (an overall yield of 22% versus 52%).

5 Discussion

This work presents the first comprehensive environmental analysis of multiple sheet metal forming processes, including electrical energy measurements, case studies, and predictive models. The levels of uncertainty in the predictive models are high; however, the aim of this analysis is to provide reasonable estimates, identify the influential parameters, and highlight trends within and across processes. Despite the uncertainty, these goals have been achieved. For instance, Figure 10 shows the effect of production number over the die lifespan on CED for different processes.

5.1 Where should research focus?

When a small number of parts is required (less than 100), the impacts of the die-set are dominant. If die-sets are found to be necessary (ISF can not be used), then reducing die-set impacts may be achieved by forming with reconfigurable discrete “pin” dies. Several authors have investigated this potential (Walczyk and Hardt, 1998; Munro and Walczyk, 2007), but these die-sets remain uncommon in industry. Alternatively, Cooper et al. (2016) highlight some options that may reduce the CED of cast zinc dies: for instance, increasing foundry furnace efficiency (e.g., grouping casting projects to allow furnace shut down during idle periods) and options further upstream like reducing the number of re-melting cycles in the recycled zinc supply chain.

As the production number over the die lifespan increases, the sheet becomes the dominant contributor to energy (CED) requirements and environmental impacts. Although some of this sheet is used in the final product, significant quantities are scrapped as part of the blanking and trimming processes (see Figure 6 and 7). For drawing in particular, the impacts of scrapped sheet dwarf those of press electrical energy

requirements. This finding suggests that researchers interested in sustainability should focus on reducing sheet scrap losses through die and blank shape innovations rather than focus on the electrical energy needed to operate the drawing press. Another option may be to reuse (without melting) sheet scrap by using the offcuts to form smaller parts. Allwood et al. (2010) present the example of Abbey Steel in the UK, a company that reuses around 10,000 t of automotive steel manufacturing scrap per year in order to make small non-critical components for filing cabinets, electrical connectors, shelving, etc. A study on the potential to cascade different scrap sizes through industries requiring smaller blank sizes could prove fruitful.

5.2 Reducing electrical energy requirements

Press electricity requirements can be significant for processes with long forming times. The total installed power capacity of all of the machines is high. The full power capacity corresponds to the maximum forming forces that the machine can generate, and these peak forces are typically only required for a small fraction of the total cycle time. This leads to low average power factors and high line currents, increasing line and transformer energy losses.

All of the processes contain a hydraulic system. As noted by Nadal et al. (2002) in a review of energy-efficient motor systems, nearly all pump applications require time-varying flow, and this variation is often done inefficiently. In the hydraulic drawing, stretch forming, and FCF presses, fixed speed motors continue circulating hydraulic fluid even during idling or low speed jogging, resulting in high baseload power. Motor speed control offers the potential for energy savings in these drive power systems. Possible solutions include DC motors where the voltage supply level can be adjusted, or electronic variable/adjustable-speed drives (VDSs/ASDs). These devices save energy by slowing a motor to match light loads. As energy use is proportional to the cube of the flow rate in the

hydraulic system, small reductions in flow can yield disproportionately large energy savings. There is evidence that in some new machines and recent retrofits, metal formers are taking advantage of motor speed control drives (MFM, 2010).

For drawing and FCF, the majority of the electrical energy is consumed during part set-up, suggesting that quicker part and blank turnovers would be an effective method of reducing per part electrical energy demand. It should be noted that in mass production, drawing presses are typically linked to automated handling systems that can reduce part set-up time to less than 3 seconds (Schuler GmbH, 1998). Flywheels are already used in mechanical drawing presses in order to reduce installed power capacities; additionally, an increasing number of press builders are looking to replace the conventional flywheel with a servomotor, which can recover kinetic energy during press deceleration (Osakada et al., 2011). Since multiple parts can be formed simultaneously using FCF, effective nesting of the dies and blanks to ensure that the tray is as full as possible would reduce per part electricity requirements. For stretch forming, batch set-up and forming times might be reduced with the addition of automatic controls rather than operators “eyeballing” the process.

In SPF, the resistive heating used to heat the press platens dominates the electrical energy requirement. By not directly heating the blank, this platen heating causes significant energy losses through convection and radiation. Directly heating the forming dies to more directly heat the blank has been explored by Schroth (2004) and found to result in per part electrical energy savings of up to 70%; however, the tooling is much more expensive. As discussed by Rossie (2015), there may also be opportunities to save energy by adding or removing thermal mass depending on the work scheduling and cycle times.

For the case of the ISF machine used in the case study, a hydraulic blank holder system runs continuously throughout the forming process. A

passive blank holding system (such as nuts and bolts or a quicker snap-fit system) would eliminate the need for this continuous power draw. As discussed in Section 4.1.1, ISF power requirements are largely independent of the forming parameters or material being formed. In order to save electricity it is therefore important to focus on reducing the forming times. Researchers must look to increase tool speeds and step sizes. Greater emphasis on appropriate motor sizing and machine architecture may lead to increased tool speeds. Allwood et al. (2016) point out that ISF requires cyclic acceleration and deceleration of several axes. As maximum motor acceleration decreases with maximum motor power (due to the larger rotor required for higher torques), the most powerful motors may not be best suited to decreasing ISF forming times.

The technologies studied in this work range from a mature technology with over 100 years of industry application (drawing) to an emerging technology still predominantly studied in research institutions (ISF). Drawing has been improved over time and has the smallest electricity requirement (for use in the forming press) of any of the technologies studied. Large reductions in drawing CED are likely to come from improving the material, rather than energy, efficiency of the press. On the other hand, improvements in motor sizing and blank holding could offer almost immediate opportunities to increase ISF electrical energy efficiency.

5.3 Other potential strategies: reusing sheet metal parts

This work has focused on the potential to increase the energy and material efficiency of forming processes. At end-of-life, there may also be potential to reform some parts into new components (Cooper and Gutowski, 2015). Tekkaya et al. (2008) demonstrate that FCF can flatten contoured sheet parts like car hoods and washing machine panels. They show that ISF can then create new shapes from these flat sheets. Similarly, Takano et al.

(2007) develop an ISF process to flatten bent sheet metal, resulting in a locally thickened area at the site of the former bend, which Takano et al. (2008) show does not significantly affect the formability of the sheet. In an analysis of the global technical potential to reuse metal components, Cooper and Allwood (2012) conservatively estimate that such methods could be employed to reuse up to 10% of the sheet metal in a car body.

6 Conclusions

This work presents the first comprehensive cradle-to-gate environmental analysis of sheet metal forming processes, providing insights to the electrical energy characteristics of the various processes and highlighting the need for research focused on reducing sheet metal waste in the forming process. It has also examined the potential for incremental sheet forming to save energy compared to drawing parts with zinc dies, finding that considerable savings are possible for production numbers over the die lifespan of less than 100 parts.

Acknowledgements

This work has been supported by US Department of Energy grant: DOE/EE-0998. We are grateful to all the car and aerospace companies for the data they provided.

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