Energy Efficiency of Sheet Metal Working Processes
Where do we stand today?

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Abstract

Due to increasing energy and resource costs at the one hand and upcoming regulations on energy and resource efficiency at the other, a growing interest of machine tool builders to the environmental performance of their machine tools can be observed today. The last decade, academic as well as industrial research groups started to assess the energy demand of discrete part manufacturing processes and indicated a significant potential for improvement [1]. In contrast to conventional machining processes (e.g. milling, turning…), (sheet) metal forming processes are still less well documented in terms of their energy demand [2]. In consequence, potential energy efficiency improvement measures for these processes are often not yet recognized. This contribution provides a short discussion on energy assessment methods followed by a structured overview of available studies on the energy demand of (sheet) metal forming processes. A range of identified energy efficiency improvement measures, suitable for these processes, is presented and quantified.

KEYWORDS: Sustainable Manufacturing; Energy Efficiency; Metal Forming Processes

1 Introduction

Taking into account the expected growth of the world's population and increasing welfare level in developing countries, the global energy and resource demand will increase significantly. Therefore, the environmental burden per unit produced should be strongly reduced in order to assure a sustainable impact level. In 2010, the industrial sector was responsible for approximately 25% of the total energy consumption in Europe [3]. The share of the different industrial sectors for the EU27 is shown in Figure 1.

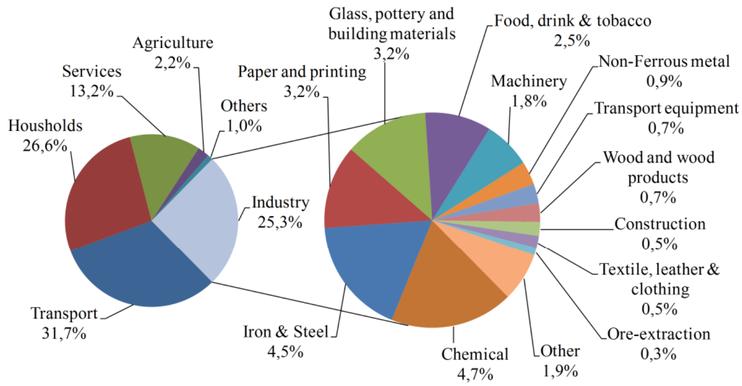

Figure 1: EU27 total energy consumption share for 2010 [3]

Manufacturing processes are responsible for a substantial part of the environmental impact of products and their impact can be expected to further increase taking into account the trend towards more energy intensive processes [4]. However, many manufacturing processes, including sheet metal forming processes, are still poorly documented and optimized in terms of their environmental footprint.

As an example, the UK metal forming sector consumes approximately 1515 GWh per year [5]. Natural gas accounts for 70% of the sector's energy consumption, with electricity accounting for the remaining 30%. While forging and fasteners sub-sectors use significant quantities of natural gas to provide the required process heat, most sheet metal operations are cold manufacturing processes. Presses and hammers consume around 20% of the sector's total electricity consumption [5]. This paper will focus on the electric energy consumption of sheet metal forming machine tools.

Bey et al. [6] indicated that the main barriers for implementation of environmental strategies in companies are a lack of information on environmental impacts, lack of expert knowledge as well as a lack of allocated resources (man power and time). On the other hand, the most important drivers, both for triggering and sustaining implementation of environmental strategies in companies, are legislative requirements, customer demands and expected competitive advantages.

In order to deal with the lack of thorough environmental analysis of manufacturing processes, the CO_2PE! - Cooperative Effort on Process Emissions in Manufacturing – Initiative [7] has been launched in 2009. This initiative has as objective to coordinate international efforts aiming to document and analyze the overall environmental impact for a wide range of available and emerging manufacturing processes with respect to their direct and indirect emissions and to provide guidelines to improve these.

2 Energy Assessment Methods

Different methods - starting from theoretic calculations until detailed process measurements and analysis - exist to determine the energy consumption of manufacturing processes. While Abele et al. [8] describe theoretic equations to calculate the energy consumption for a wide range of production processes, Overcash et al. [9] propose a generic methodology to gather unit process life cycle inventory data using rules of engineering and industrial practice. Within the CO_2PE!-Initiative, Kellens et al. [10] developed a methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI). Finally, part two of the emerging ISO 14955 standard [11] on environmental evalutation of machine tools provides guidelines how to measure and quantify the energy demand and efficiency of machine tools in line with this methodology.

Duflou et al. [12] present a comparison of the previously mentioned methods as well as the available Life Cycle Inventory data in commercial databases. The authors observed large discrepancies on the energy demand and related environmental impact of discrete part manufacturing processes obtained by different assessment methods. While theoretical calculations often result in large underestimations, most energy values for manufacturing processes specified in commercial LCI databases show significant space for improvement [12].

3 Energy Assessment of Sheet Metal Forming Processes

Ingarao et al. [2] presented an overview of the state of the art of energy and resource efficiency of sheet metal forming technologies, covering the total life cycle starting from raw materials production up to recycling technologies. This section provides a structured overview of available energy assessments of discrete sheet metal forming processes.

3.1 Air Bending

Kellens et al. [13] as well as Santos et al. [14] investigated the energy consumption of air bending processes and observed that the standby energy is substantial. On the one hand, due to diverse operator activities, the time share of the standby mode (mode 1) is very high, as indicated in Figure 2. On the other hand, the power levels during the standby mode are significant, ranging from 1.4kW to 5kW for conventional hydraulic press brakes with a maximum capacity between 80 and 170 ton. Figure 3 shows the power levels of four hydraulic (A-D) and one electric (E) press brake during multiple production modes.

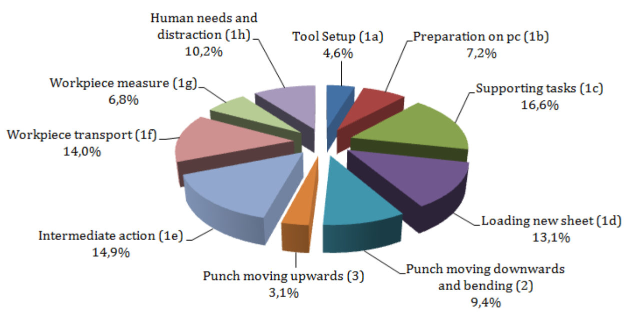

Figure 2: Time distribution of the production modes for air bending [13]

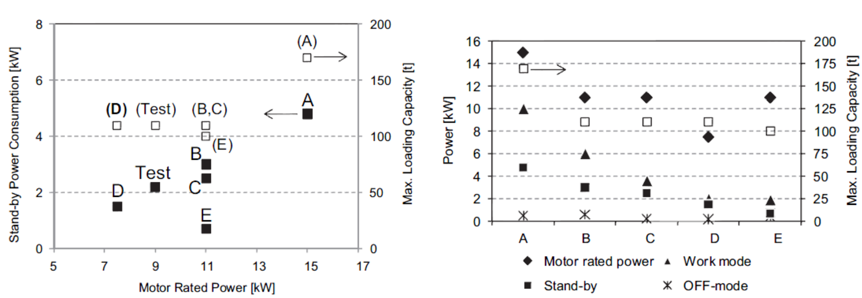

Figure 3: Power consumption of air bending machine tools with different capacities [14]

3.2 Deep Drawing

While Doege et al. [15] investigated the energy consumption (Table 1) of three deep drawing presses with different press capacities, Lohse et al. [16, 17] determined the energy efficiency (the ratio between the useful forming energy and total energy input of a complete working cycle) of hydraulic deep drawing presses. When regarding a whole press cycle which consists of fast motion down, pressing, force relief and fast motion up, the energy efficiency of the investigated machine tool is 11.8%. Figure 4 shows the power profile as well as the distribution of forming work and heat losses of a 1600 kN press during different production modes. Similar investigations on 2500 and 6300 kN presses are presented in [16] and [17].

	Small Press	**Medium Press**	**Large Press**
Capacity [kN]	650	3500	38000
Measuring Period [h]	20	40	20
Energy Consumption [kWh]	30	315	2000
Strokes / minute [#]	70	28	12

Table 1: Energy consumption of different deep drawing presses [15]

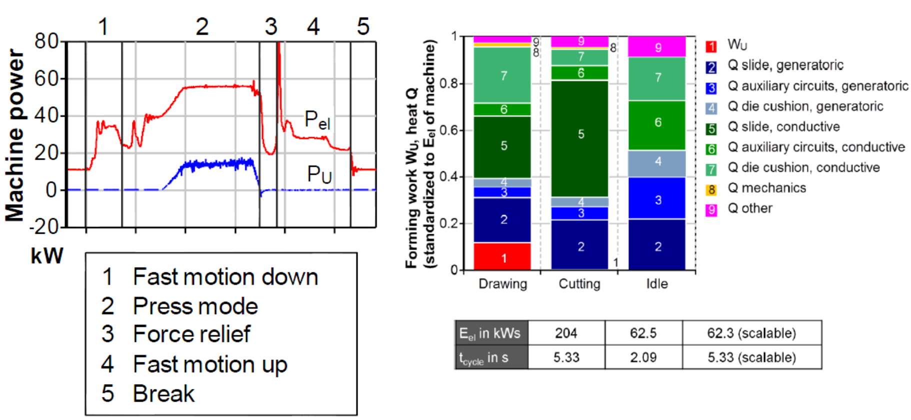

Figure 4: Power profile and energy distribution of a 1600 kN press [16]

In order to increase the energy efficiency of the investigated machine tools, the authors indicate that, where possible, force and stroke should match well when combining tool and machine tool (press). Furthermore, tool closing and opening strokes should be kept as short as feasible and electric motors should stop in breaks where possible [16, 17].

3.3 Hydro-Forming

As shown in Table 2, Matwick [18] roughly estimated the power consumption of three classes (e.g. press capacity) of sheet hydroforming processes.

	Class 1	**Class 2**	**Class 3**
Capacity [tons]	1200	3000	4000
Power [kW]	140	250	300

Table 2: Press classes for sheet hydroforming processes [18]

Morphy [19] investigated and compared the efficiency and effectiveness of pressure sequence hydroforming (PSH) with respect to high pressure hydroforming (HPH). While Figure 5 shows the designs and process chains of both compared products (e.g. similar function and tube size), Table 3 provides an overview of the main results of the comparison. In case PSH can fulfill all functional requirements, PSH can offer signifant benefits in terms of energy consumption, cycle time as well as required floor area.

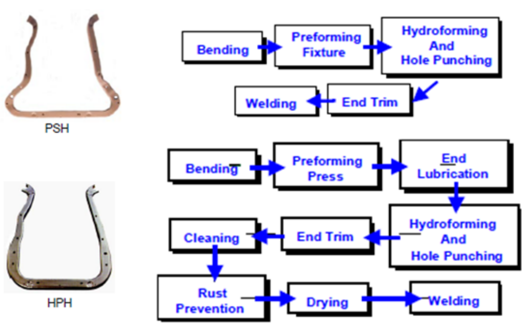

Figure 5: Designs and process chains [19]

	PSH	**HPH**
Required forming pressures Used presses Power demand	48 MPa 1100 tonne press 94 kW	152 MPa 3500 tonne press 630 kW
Cycle Time	22 seconds	34 seconds
Energy consumption / part	0.7 kWh	5.8 kWh
Required floor area	240 m^2	1090 m^2

Table 3: Comparison of PSH and HPH process chains [19]

3.4 Cold Rolling Forming

Paralikas et al. [20, 21] investigated energy efficiency optimization measures for cold roll forming processes. Using analytical as well as computational modeling approaches, the authors demonstrated a robust design optimization of a U-channel profile and quantified the effect of applied process parameters on the total process energy efficiency. From energetic point of view, the dominant process parameters are the roll gap, roller radius and bending angle with 31, 25 and 24% of influence respectively.

3.5 Punching / Blanking

Ingarao et al. [22] investigated the electric energy demand of two types of punching machine tools. While machine tool A (Figure 6 left) has a fixed hydraulic pump and maximum load capacity of 220 kN, punching machine tool B (Figure 6 right) has a variable pump system (servo drive with frequency steering) and a load capacity of 200 kN. Furthermore, the authors quantified the influence on the electrical power demand of the tool size, material as well as sheet thickness.

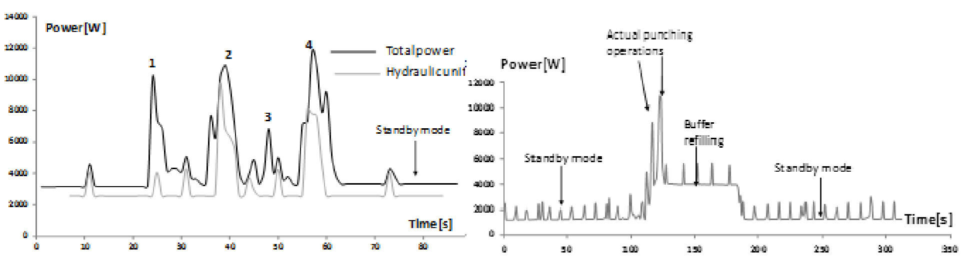

Figure 6: Power profile for punching machine tools A (left) and B (right) [22]

For blanking processes, six press classes were defined by Matwick [18]. The related machine tool capacities as well as estimated power demands are listed in Table 4.

	Class 1	Class 2	Class 3	Class 4	Class 5	Class 6
Capacity [tons]	50	100	200	400	600	1000
Power [kW]	100	150	200	300	400	500

Table 4: Press classes for blanking machine tools [18]

3.6 Stamping

Shi et al. [23] performed an energetic assessment of stamping processes. While the left side of Figure 7 shows the electric power profile of a 2000 kN stamping machine tool, the increase of electric power demand for an increasing number of strokes per minute (SPM) is presented at the right side of Figure 7.

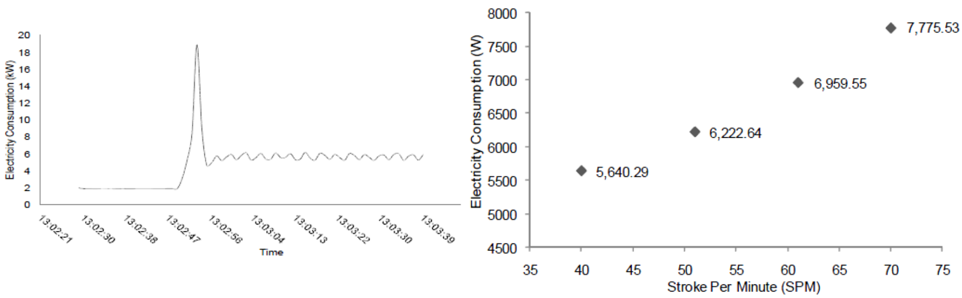

Figure 7: Power profile at 55 SPM (left) and average power consumption in fucntion of the strokes per minute (right) for a 2000 kN stamping machine tool [23]

3.7 Incremental Forming

Dittrich et al. [24] presented an exergy analysis of incremental sheet forming (ISF) processes and compared two ISF variants (single and double sided) to conventional forming and hydro forming processes. The single and double sided ISF processes consume on average 610 and 740 Watt respectively. The authors indicated that from environmental perspective ISF processes are advantageous for prototyping and small production runs up to 300 parts [24].

Branker [25] analysed the influence of multiple process parameters (e.g. feed rate, step down, tool size and type of lubricant) on the Single Point Incremental Forming (SPIF) energy consumption while producing an aluminium bowl on a Bridgeport GX 480 vertical mill. Average standby and operational power levels were 639 and 778 watt respectively. Most influencing parameters were the feed rate (Figure 8 right) and step down (Figure 8 left).

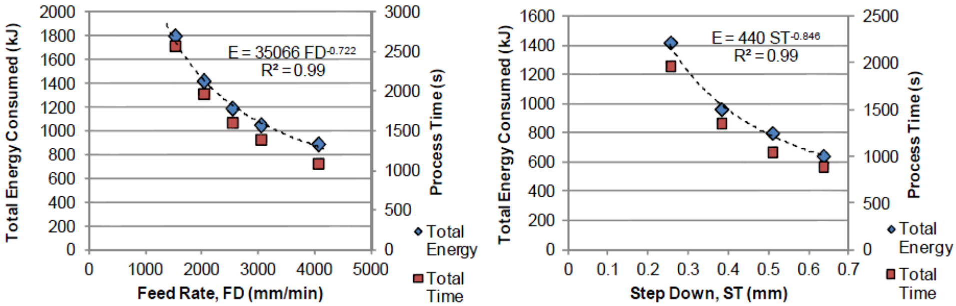

Figure 8: Influence of the feed rate and step down on the SPIF energy consumption [25]

Ingarao et al. [26] compared the three available SPIF machine tool architectures from energetic point of view (Table 5). While a CNC milling machine tool set-up (measured on a MAHO MH 600C) has a very low energy efficiency, the dedicated AMINO set-up has the lowest power demand. However, the analysed robot set-up (Kuka KR210) has the lowest total energy consumption due to its higher process speed and thus shorter forming time. Next to proper process set-up (machine tool) selection, tool-path optimization as well as maximizing the feed rate help to reduce the total process time and related energy consumption. Furthermore the authors developed a parametric process model to estimate the SPIF energy consumption for the robot set-up based on the part design.

Power [W]	**CNC milling machine tool set-up**	**Six-axes Robot set-up**	**AMINO set-up**
Start-up/Shut Down	800	220	-
Standby	2000	630	-
Operational	3000	619 – 864	379

Table 5: Average power demand of different SPIF set-ups [26]

4 Energy Efficiency Improvement Measures

Once the energy consumption of the use phase of a manufacturing process has been documented, potential measures to improve this energy demand can be investigated. Among others, the Cecimo Self Regulatory Initiative [27] and Blue Competence Machine Tool Initiative [27] provide lists of potential environmental improvement measures at machine tool and process chain level. An non-exhaustive overview of specific energy efficiency improvement measures for (sheet) metal forming processes is provided in annex B of the ISO 14955 standard [11]. A summary of the most promising measures, together with a rough estimation of their potential energy savings, is listed in Table 6.

Improvement Measure	**Hydraulic Presses**	**Servo Presses**	**Mechanical Presses**
Minimization of moved masses	3 to 6%	3%	3%
Use of passive die clamping systems	3 to 6%	3 to 6%	< 3%
Optimisation of installed motor power	3 to 6%	3 to 6%	3 to 6%
Use of energy efficient pump-motor units	> 6%	> 6%	> 6%
Switch off non-required sub-units	3 to 6%	3%	3%
Efficient control of oil temperature & viscosity	3 to 6%	3 to 6%	< 3%
Leakage control and low flow resistance	3 to 6%	3 to 6%	< 3%
High efficient auxiliary pressure generation	6%	6%	< 3%
Variable, demand based, lubrication flows	-	3 to 6%	3 to 6%
Thermal management of cooling devices	6%	6%	6%
Avoid power supply oversizing/overloading	3 to 6%	3 to 6%	3 to 6%
Use power convertor/inverter systems with power factor correction	3 to 6%	3 to 6%	3 to 6%
Thermal management of control cabinet	3 to 6%	3 to 6%	3 to 6%
Optimized compressed air system	3 to 6%	3 to 6%	< 3%
Provide energy demand information to the machine tool operator	6%	6%	6%
Minimize non-productive time	3 to 6%	3%	3 to 6%
Automatic operating state switching	6%	6%	< 3%

Table 6: Overview of expected reduction of energy consumption for hydraulic, servo and mechanical presses for different design and operational measures [11]

4.1 Generic Categorization of Improvement Measures

Different strategies can be considered while aiming for the reduction of energy and resource consumption and related environmental impact at a unit process level. Kellens [28] presented a generic improvement categorization starting from three main categories: proper process and machine tool selection; optimized machine tool design; as well as optimized process control. While the first and last category are mainly controllable by the process planner or the machine tool operator, the original equipment manufacturer (OEM) or machine tool builder has a dominant influence on the machine tool design. Connected to these three main categories, thirteen sub-categories, shown in Figure 9, can be identified. Interrelationships between different sub-categories are indicated as dashed lines.

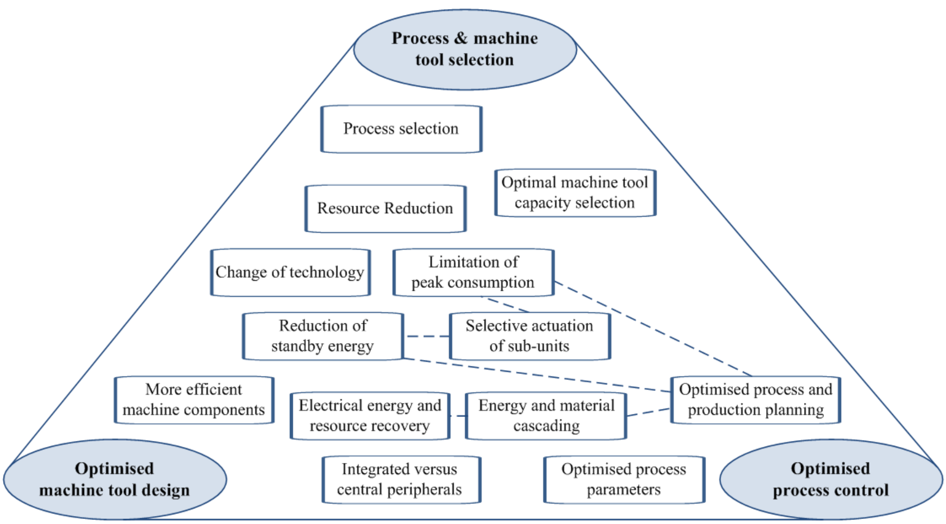

Figure 9: Improvement measure categories at unit process level [28]

4.2 Improvement Measures for Sheet Metal Forming Processes

Starting from the generic categorisation of improvement measures shown in Figure 9, this paragraph describes some examples of quantified improvement measures for sheet metal forming processes.

Process / Machine Tool Selection

As indicated in Section 3.3, Morphy [19] compared the energy efficiency of pressure sequence hydroforming (PSH) and pressure hydroforming (HPH) processes. While Ingarao et al. [29] compared the theoretical energy consumption of stamping and SPIF (Mazak vertical milling machine tool) starting from the applied forces, Dittrich et al. [24] performed an exergy comparison of both single and double side incremental forming, conventional forming (plastic and cast iron die set), and hydro forming processes. The production of die sets is taken into account in this study. As shown in Figure 10, for small production runs, the exergy demand of both ISF methods is significantly lower compared to conventional forming (e.g. deep drawing) and hydroforming processes. Conventional forming (cast iron die set) and hydroforming processes become advantageous starting from 200 and 560 parts respectively [24].

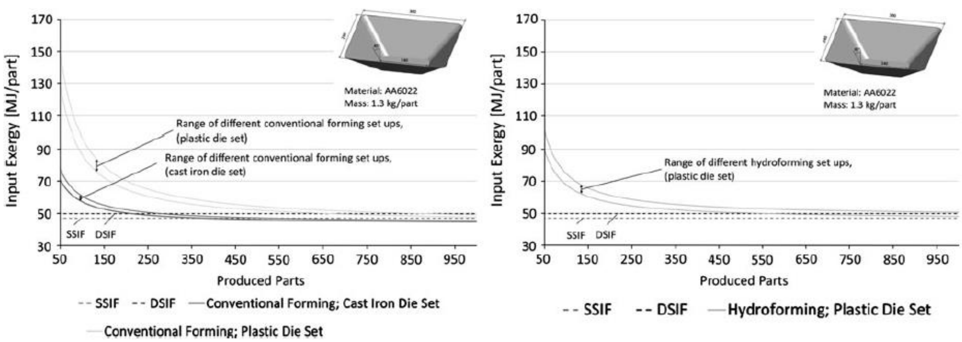

Figure 10: Comparison of the exergy demand of different metal forming processes [24]

Optimal Machine Tool Capacity

Due to the higher required fixed power levels for machine tools with increasing maximum capacities, proper selection of machine tools (e.g. using machine tools as near as possible to their maximum capacity) will lead to energy consumption savings. As an example, Figure 11 shows a difference of around 20% in energy demand for a 1350 kN press brake compared to a press brake of 800 kN performing a similar task of 400 kN.

Change of Technology

The last decade, a shift from full hydraulic presses towards servodriven hydraulic systems or even full electric presses can be observed [e.g. 30]. As shown in Figure 11 and Table 7, switching from conventional, continuously active hydraulic systems for air bending towards frequency covertor steered servomotor driven pumps with direct control of hydraulic pistons, reductions up to 60% in power demand during productive modes can be observed. Taking into account also the non-productive modes (e.g. standby modes), this corresponds to approximately 25% of the total production energy.

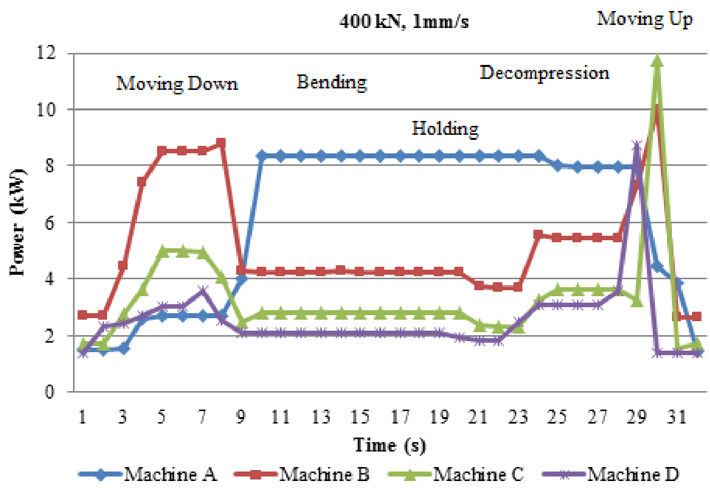

Figure 11: Power profile of four different press brakes with a bending load of 400 kN and a bending speed of 1 mm/s [13]

Machine Tool	Capacity	
A	800 kN	Fixed hydraulic pump
B	1350 kN	Servo driven hydraulic pump
C	1350 kN	Frequency steered, servo driven hydraulic pump
D	800 kN	

Table 7: Overview of four different press brake configurations [13]

Optimized process parameters

From operator perspective, environmental aware process parameter selection can further limit the energy and resource consumption and related environmental impact. While Branker [25] indicated the influence of the applied feed rate and step down for SPIF processes (Figure 8), Kellens et al. [13] presented significant energy savings up to 50% for increasing bending speeds of press brakes.

5 Conclusions

This paper presents an overview of the state of the art in energy efficiency of sheet metal forming processes. A short overview of available energy assessment methods is provided and documented energy analyses of sheet metal forming processes are presented. With execption of air bending and single point incremental forming (SPIF) processes, sheet metal forming processes are still not (well) documented in terms of their energy demand. In consequence, substantial space for improvement in data collection can still be expected for this process category. Related to this, the potential for effective reduction of the energy consumption in the involved industry is estimated to be significant and deserves intensification of the R&D efforts dedicated to this aspect of process and machine tool design.

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