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Towards Benign Metal-Forming: The Assessment of the Environmental Performance of Metal-Sheet Forming Processes

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1. Introduction

In the last decade, significant attention has been devoted to the assessment of the environmental impact of manufacturing processes and machine-tools, defining the most important factors to be covered and proposing methodologies to support the analysis of their individual contributions. The work published has established that the environmental impact of a manufacturing process is mainly affected by the consumption of 3 types of resources, namely:

1. The full set of resources used to obtain the machine-tool, accounted as input-output substances associated to the components production and their assembly (materials- and manufacturing processes-related);
2. The electricity required during operation, accounted as the specific process energy (SPE) related to the main functionality of the machine-tool;
3. Other process- or operation-related resources, apart from electricity, accounted as input-output substances associated to the use of the machine-tool (consumed directly in the process, by auxiliary systems during operation or in maintenance operations).

Most of the studies dealing with this triangular perspective focus the analysis of chipping processes (Dietmair & Verl, 2010; EBM, 2010; Gutowski et al., 2006; Kuhrke et al., 2010; Pusavec et al., 2010a,b; Rajemi et al., 2010). Other pure metal forming processes, such as chipless-shaping processes, typically involve no significant material waste or consumables usage, and the savings on the electrical consumption of the machine-tool become the dominant factor to analyse during the use-stage (Santos et al, 2011). As advanced by Gutowski (Gutowski et al., 2006), the total energy required for operation of a machine-tool is not constant, as many life-cycle assessment (LCA) tools assume, and instead the system total electricity consumption, $P_{active, System}$, should be decomposed in a fixed and a variable parts, according to Eq. (1):

$$P_{active, System} = P_0 + k\dot{v} \quad (1)$$

where P_0 is the fixed part corresponding to the total stand-by power [kW], \dot{v} is the rate of material processing, typically in cm^3/s , and k is a constant provided in kJ/cm^3 .

Additionally, from Eq. (1), the SPE would be built as indicated in Eq. (2):

$$B_{elect} = \frac{P_0}{\dot{v}} + k \quad (2)$$

While the constant part is used to insure the active response of sub-systems, such as driving controls, exhaustion or cooling apparatus, and is independent of whether or not a part is being produced, the variable part corresponds to the energy needed to produce a work-piece and is typically proportional to the amount of material being processed or to the type of work.

As demonstrated by Santos (Santos et al, 2011) for pure forming processes with discrete loading, such as bending, the maximum value of the variable part is limited by the machine characteristics, affecting the throughput. On the other hand, this is the theoretically constant value to which the SPE model would tend to, considering the fixed consumption would be shared by an infinite throughput. In real scenarios, the rate between constant and variable contributions associated to a production cycle, as well as their respective values, is mostly dependent on the system technology. However, the full implications of technology to the environmental profile of the machine should be attained in terms of the contributing triangle referred and not only the energy-consumption during use of the machine-tool.

Another point is the guiding for environmental improvement, as the environmental impact assessment requires the application of specific methods and tools. Life-cycle assessment (LCA) is the reference tool for environmental profiling of products and processes, as it is the most effective tool for this purpose and permits the most advanced environmental analysis possible. Every LCA methods use qualitative, quantitative or semi-quantitative analysis, although the quantitative form is considered more suitable for detailed LCA studies (Curran, 1996; Hochschorner, 2003). However, LCA tools can be time and work consuming and thus have significant costs.

In recent years, there has been a trend for the development of simplified methods for LCA. These are quantitative or semi-quantitative methodologies aiming to give quick answers and suggestions. Although these methods tend to be very universal and wide-ranging, given the broad applicability of these methodologies and the strong emergence of its use, they have a strong customization potential. In fact, these simplification techniques can be adapted to provide 'customized' or 'tailor-made' perspectives in studies of specific systems or sectors, enabling to include system-specific principles and practices more relevant and appropriate to the interested LCA end-user, while still producing valid and robust results, and keeping the LCA basic conditions regarding scope and methodology (Bala, 2010; Curran, 1996). In line with this, Hochschorner (Hochschorner et al, 2003) highlighted the importance of the method applicability to the field of application as the most important selection criteria of the proper LCA method to adopt, in order to deliver the required information.

Regarding this, it is important to highlight the interesting work followed by the CO2PE initiative (Kellens et al., 2012), which has been working on the definition of a methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI), i.e. on the deep analysis and quantification of the manufacturing processes environmental impact. To ensure optimal reproducibility and applicability, documentation guidelines for data and metadata are included in this approach. Guidance on the definition of a functional unit and a reference flow as well as on the determination of system boundaries meets the generic LCA goal and scope definition requirements of ISO 14040 and ISO 14044. Developed with the purpose to provide high-quality life-cycle inventory (LCI) data for manufacturing unit processes, this work seems to fit the needs of methodology standardization for the machine-tool use-stage analysis.

This chapter provides an overview on the assessment of the environmental impact of metal-forming processes and machine-tools. The most important factors to be considered are discussed and some methodologies supporting the analysis of the individual contribution of energy consumption during process are presented, as this is still considered as the main detractor. Process categorization criteria and accurate modelling of the energy consumption per category are here highlighted as the basis for high quality quantitative inventory data to achieve reliable environmental profiling. Pure metal forming processes, such as bending, are covered. Overall and sub-systems accounting strategies are presented, using the case of Laser cutting as an example of multiple sub-systems with similar contribution to the total energy consumption. The main findings and conclusions, as well as some strategies favouring the environmental performance of the manufacturing processes, are here discussed.

2. Methodologies used

The strategies for improvement expected from the environmental profile assessment of a process shall be based on the comparative analysis between alternative production scenarios. Relevant technologies and application ranges have been selected, considering the respective technology/application market share. Comparative studies were followed with a pre-defined job and application ranges (material, shape, process quality,...), and under similar utilization modes.

Regarding data collection, particularly on preliminary process evaluations, it seemed realistic to start focusing on energy consumption and any main consumable. The same measuring system and accounting methods were used throughout the comparative studies followed.

Special attention was dedicated to the accounting methods and assessment methodology to use. A wide discussion has been followed about the limitations of the non-standardized methodologies and the impact of the quality of the inventory and main indicators to the reliability and standardization of environmental profile assessment results. As presented in a previous work (Azevedo et al, 2010), for the purpose of the analysis of the environmental profile of a machine-tool, the contribution of the different main inputs to the overall impact

shall be analysed relatively to each other. On the other hand, the detailed analysis per environmental impact category should consider absolute values, in order to reveal those categories to which the process is potentially more detrimental to, and which main input contributes most to it, in order to properly inform about the real extent of the impact. This was also the strategy here adopted.

2.1. Data collection

Manufacturing processes analysed were metal bending and Laser-cutting. In both cases, no other process- or operation-related resources, apart from electricity, were consumed, but the influence of the hydraulic oil needs during the equipment's lifetime was considered in the LCA analysis of a conventional press-brake used for bending. In the case of the Laser cutting machine, with individualised sub-systems, power consumption measurements were followed in parallel for the 3 main sub-systems, namely the Laser source, the chiller and the control unit (Oliveira et al, 2010).

The energy consumption data were acquired with a Janitza Power Analyzer, model UMG 604, a measuring system able to measure and calculate multiple electrical variables on 3-phase AC systems. The system was configured to record current, voltage, and power factor per line every 1 s, installed in the machine-tool's electrical cabinet; accounts over 24 h for each test have been followed. In the used configuration, the system is capable to measure low-voltage systems up to 300 V conductor to earth and currents up to 60 A, with maximum measuring uncertainties of ± 0.50 V and ± 0.15 A, respectively, over long periods of time (Santos et al, 2011).

The yearly consumption of hydraulic oil was taken from the Preventive Maintenance Plan provided by the machine-tools local manufacturer involved in the time-studies (Adira S.A., 2010).

2.2. Accounting and LCA methodologies

As advanced, there are still no specific tools and methodologies for the characterization of the environmental profile of a manufacturing process. This is being taken by research groups and associations, such as the CO2PE initiative previously referred, but still much as to be done on the standardization of methods and quality of the inventory data currently available. As referred, the particular system technology being used for the process, i.e., the type of machine-tool available, as well as the utilization mode during production, also plays an important role on the accounting of energy consumption during process, although this has been neglected on the common LCI databases.

All environmental analysis generated in this framework was followed by application of the Eco-Indicator 99 (H,A) method, using SimaPro 7.0 with Ecoinvent 2.0 unit processes as LCI database (Pré-consultants, 2010a,b). LCI datasets of secondary metals have been used whenever applicable on the equipment-related resources. The main inputs related to the use phase, electricity and hydraulic oil, were distinguished as different use phases, to assist their individual impact during the analysis. The LCA outcome results from Single Score analysis.

3. Critical factors in the analysis of main environmental impact contributors

Regarding the SPE contribution, the differentiation between metal manufacturing processes involving material removal and deposition from those pure forming operations, understood as discrete loading operations, has been proposed (Santos et al., 2011). In the different studies supporting this work, comparison and modelling of the electricity consumption data during process with systems of different technologies, and the influence of production use scenarios, were discussed based on time studies followed at industrial users. For discrete production cycle operations, such as bending, the definition of a specific exergy reference unit was proposed, since the units typically associated to manufacturing processes, generally described per unit of material processed, were considered not suitable. In this work, direct process categorization criteria such as system technology, maximum loading capacity and production scenario have been proposed.

On the other hand, in what refers to system technology, overall vs sub-systems (energy-consuming or not) strategies for data collection and accounting were adopted. For bending, the overall approach was used in the analysis of the press-brakes, while for the laser cutter, parallel analysis of 3 main sub-systems was followed. This latter case is in line with the current trend to more efficient power technologies and modular design, with no single dominating consumer sub-system but on a set of sub-systems with comparable energy consumption levels, which justifies the sub-system approach. In what concerns the SPE assessment, this is definitely the approach to adopt targeting the identification of main contributors, even if the total SPE value is the one to be final accounted. This problematic is patent on the following case-studies analysed.

3.1. System technology impact: Sheet metal bending

When compared to other manufacturing processes, such as chipping, coating or cutting, the effective loading time per production cycle during bending is relatively short and the specific rate at which the load is applied is not a significant process parameter. In turn, the analysis of the energy needs should focus on effective energy values in alternative to the time-dependent power parameter value.

The scans in Fig. 1 expose the referred discrete loading character inherent to bending, and the influence of machine-tool technology in the temporal evolution of power and energy consumed per operation cycle. In the case of bending, and according to the time scans presented in Fig. 1, the total energy consumption per bending cycle can be modelled according Eq. (3):

$$B_{elect} = P_{idle} \cdot \Delta t_{idle} + B_{approach} + P_{bending} \cdot \Delta t_{bending} + B_{return} \quad (3)$$

where, P_{idle} is the active power consumed during stand-by mode, being technology-related, and $P_{bending}$ is the active power consumed during loading, here proposed to be modelled according to Eq. (4):

$$P_{bending} = P_{0-bending} + c \cdot F_{bending} \quad (4)$$

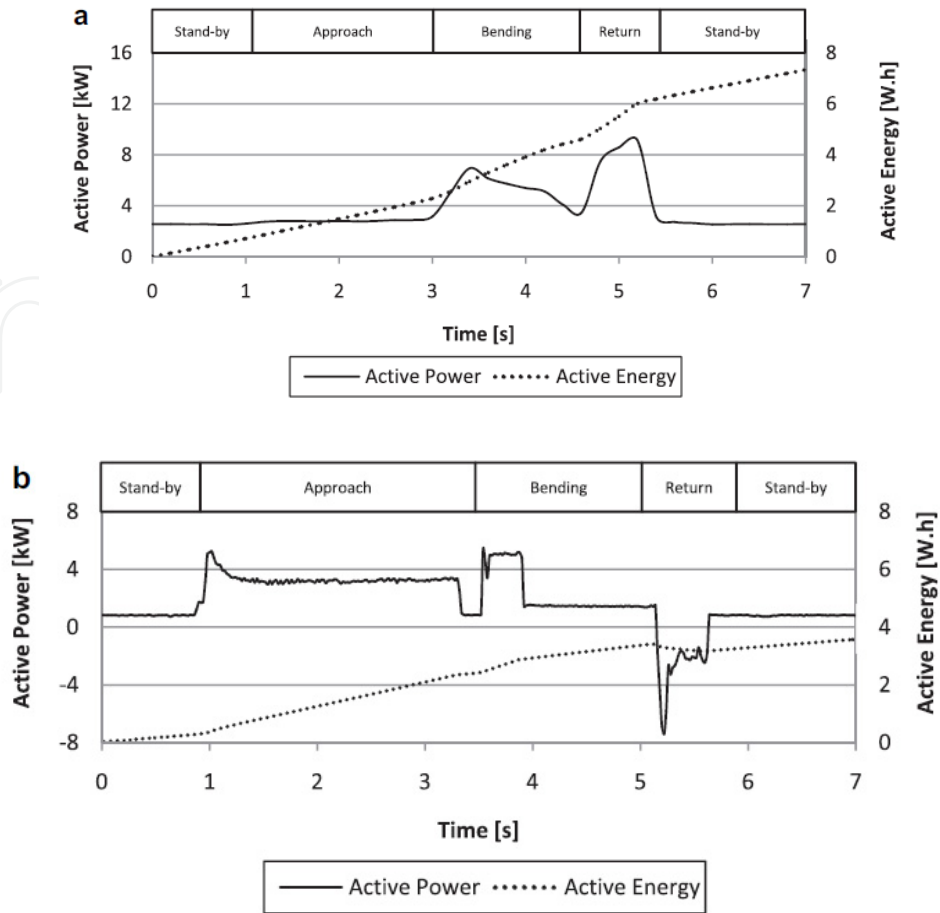


Figure 1. Examples of active power and active energy per bending cycle recorded for: a) a hydraulic press-brake and b) an all-electric press-brake.

This model is built according to Eq. (1) proposed by Gutowski (Gutowski et al., 2006), but adapted for discrete loading manufacturing processes, where, $P_{0_bending}$ stands for the power required at a zero load cycle, c is a constant in kW/t, corresponding to the positive power rate needed to sustain a theoretical continuous load increase, and $F_{bending}$ would take the real load value pre-defined for production.

However, for such discrete loading operations, the process rate must be described as a function of the frequency of production cycles, instead of the amount of material removed or being processed. In this perspective, Eq. (2) should take the form proposed in Eq. (5):

$$B_{elect} = \frac{P_{idle}}{n} + q \quad (5)$$

where n corresponds to the throughput in cycles/h.

Following the previous discussion on the fixed and variable contributions of the specific process energy, constant q represents the cycle peak energy obtained at a pre-defined process load and loading time, excluding the fixed contribution, while the variable contribution $\frac{P_{idle}}{n}$ considers the total cycle time, which is dependent on the production

throughput, in opposition to the loading time in the chipping processes. From this, it can be concluded that the actual energy and usage of each machine are essential to estimate the SPE required for bending operation or any other discrete loading operations.

The SPE as a function of the throughput was estimated for a set of hydraulic and all-electric press-brakes based on real consumption data measured directly on the machines. Figure 2 shows the estimation models obtained for all machines, working at the highest used loading capacity during the study and with a maximum throughput value of 720 cycles/h, as this is the theoretical limit for a machine working continuously at the smallest cycle time observed (5 s).

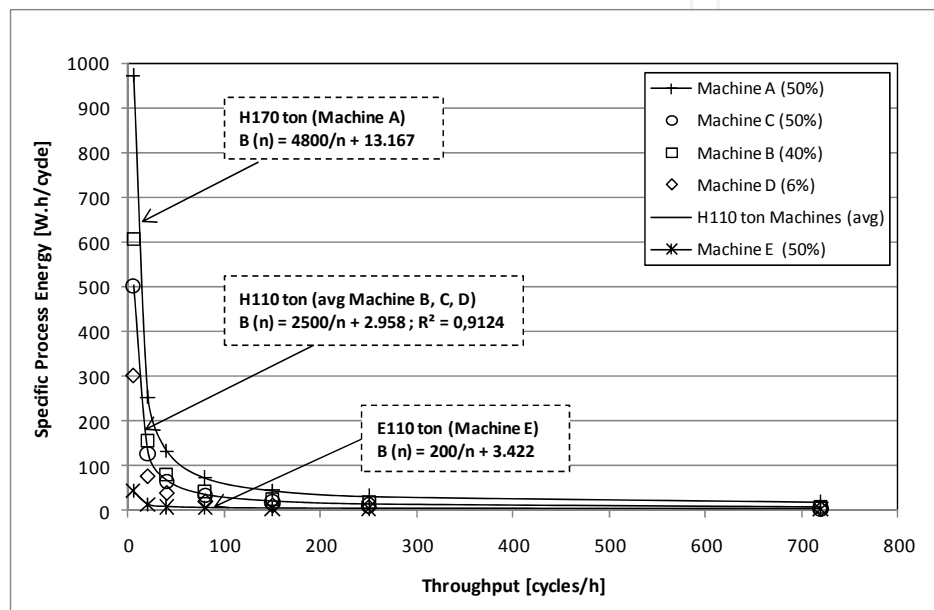


Figure 2. Specific process energy (SPE) during bending as a function of throughput, obtained from energy consumption data measured directly on a set of bending machines (n: throughput [cycles/h]; Hxxx: hydraulic technology and Exxx: all-electric technology, indicating the respective maximum bending capacity; xx%: capacity loading tested in a specific machine).

In this perspective, the following principles were proposed for the modelling of the SPE during metal-sheet bending:

- The reference unit to use is the production cycle;
- The main driving technology must be used as process categorization criteria;
- Parameterization of the SPE, for each category, is a function of the throughput.

From this, the categorization criteria proposed to be used for bending and similar discrete chipless-shaping manufacturing operations in general are the type of operation, technology, maximum loading capacity and usage scenario. Regarding the usage, typical throughput values for 3 main usage scenarios installed for bending (robot-assisted, manual-intensive and manual-discrete) have been appointed. Table 1 resumes the energy consumption values per bending technology category and usage scenario proposed to be considered for the estimation of electricity consumption related to the bending operation. These values can be

used in LCI databases, in alternative to the theoretical values typically adopted, often even associated to generic manufacturing work (Ecoinvent Centre, 2010). These data should be applicable to all types of material to be worked, as they are categorized on a bending capacity basis. The potential energy savings related to the selection of the driving system technology and the motor rated power installed were quantified from the estimated SPE values and are also here included.

<i>Specific Process Energy (SPE)</i> [W.h/cycle]	<i>Equipment Usage Scenarios</i>		
<i>Technology Category</i>	<i>Manual-discrete</i> (n=20)	<i>Manual-intensive</i> (n=80)	<i>Robot-assisted</i> (n=250)
I. Bending, hydraulic, 170 t	253.2	73.2	32.4
II. Bending, hydraulic, 110 t	128.0	34.2	13.0
III. Bending, electric, 100 t	13.4	5.9	4.2
<i>Potential energy savings</i>			
Technology-related (III vs II)	90%	83%	67%
Motor rated power-related (II vs I)	49%	53%	60%

Table 1. Specific process energy values related to bending operation, as a function of technology and usage scenario, and comparative analysis in the form of potential energy savings.

Particularly for irregular and/or low usage scenarios, the electric-based drive technology is to be recommended, as this might lead to energy savings of about 90% when compared to an all-hydraulic system, for a similar loading capacity machine, while the potential savings tend to be reduced for more intense usage scenarios. Nevertheless, even for the highest robot-assisted production scenarios, energy savings as high as 67% could be achieved with electrically-driven systems when compared to the hydraulic ones, for similar loading capacities installed.

As advanced, apart from the SPE, technology also determines the type and amount of other consumables during operation. In the case of a hydraulic press-brake, hydraulic oil is a technology-specific resource essential for its operation. The environmental impact profile related to the oil consumption is significantly affected by its no-renewable character, as this is a standard crude oil by-product, typically incinerated at the end-of-life. Figure 3 shows the contributions of the Assembly-phase and Use-phase inputs (Electricity and Oil) to the environmental profile of a hydraulic press-brake, described per different middle-point impact categories. A lifetime of about 15 years was assumed, and the contribution of an end-of-life scenario has here not been accessed. The most probable machine-tool end-of-life scenario is reutilization as second-hand which, in practice, would represent an extension of the lifetime, reflected by an increase on the use-phase inputs, i.e. SPE and hydraulic oil contributions.

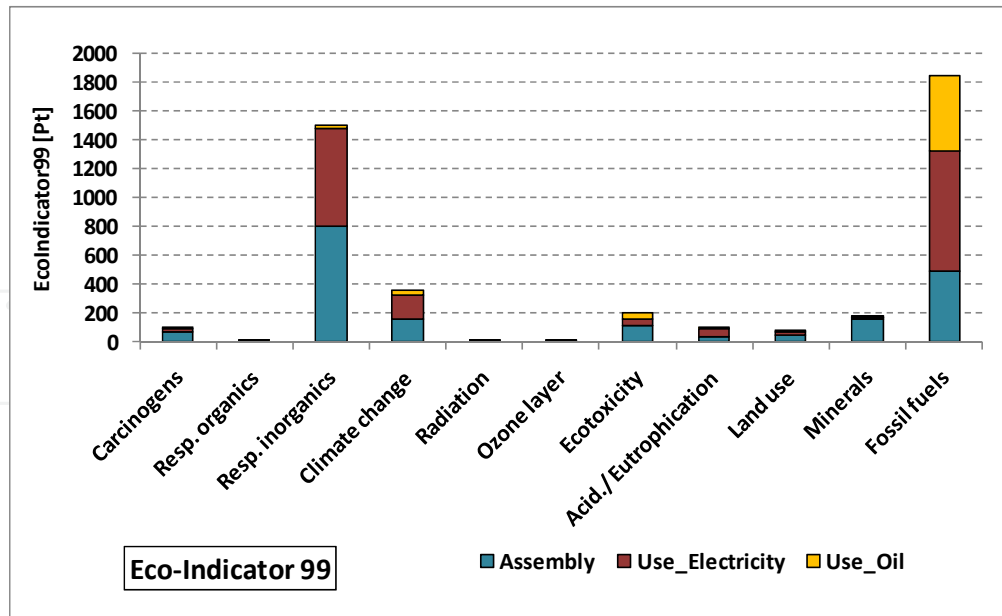


Figure 3. LCA results of the Assembly-phase and Use-phase (Electricity and Oil) inputs used for an hydraulic press-brake, per impact category (middle-point).

These results make evident that the contribution of the hydraulic oil used to the environmental impact of such machines should not be neglected. The relative contribution of the oil consumption to the global environmental impact of the machine is higher than 20%, in at least 2 of the 11 middle-point impact categories analysed. The main impact of the oil consumption, in absolute value of the indicator, is on the depletion of fossil fuels, and, in this category, the impact is similar to that of the total of assembly resources incorporated in the machine, which is considered quite significant.

3.2. Sub-system approach on SPE accounting: Sheet metal cutting

In the case of a Laser-cutter, the Laser energy source and the cooling system determine its overall integration of components and energy consumption and, thus, their analysis is essential to characterize the environmental profile of the Laser cutting process. The recent Fiber Laser (FL) technology has been compared with the well-established CO₂-Laser (CO₂). While the technical benefits related to the integration of fewer components are intuitive to promote the environmental performance of the FL technology, the strategies for energy savings are not that evident and there is still some room for improvement (Oliveira et al, 2011). Besides the Laser and cooling units, other important electrically fed subsystems, such as the general control unit (including the motorized head positioning) and the exhaustion system, should not be neglected on the analysis of the energy demand of a Laser cutter, although this later has not been actually measured in this work.

Figure 4 presents the SPE results obtained from analysing 3 equipments of FL and CO₂ technologies, in similar utilization conditions and for a similar job (1 mm steel sheet). The technology influence on the SPE is also here made evident.

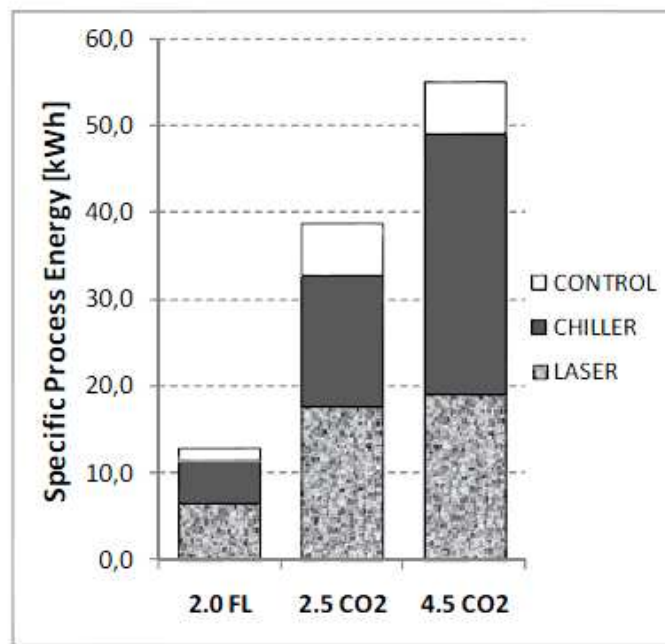


Figure 4. Specific process energy (SPE) observed for the Laser cutting process, showing relative contribution of the main sub-systems per equipment type (FL: Fiber Laser technology; CO2: CO2-Laser technology). Reference is 1 mm carbon steel sheet processing for 1 h.

Regarding the individual contribution of each main sub-systems in CO2 equipment, the chiller unit of a 4.5 kW machine was seen to be responsible for more than 50% of the energy demand, contradicting the assumption that the Laser source dominates the total energy consumption of these machines (Devoldere et al, 2006). In what concerns to the FL equipment, the energy benefits were clear:

- The higher global efficiency of the FL technology provided for a reduction of at least 1/2 on the SPE of the cutting process of thin sheets;
- The energy consumptions of both Laser and chiller units were significantly reduced. Lower cooling requirements result from the lower Laser input power and reduced energy losses.
- The contributions of the 2 main electrical sub-systems (Laser and chiller) are expected to bein the same order to that of the control unit.

In resume, FL technology brings down the Laser and chiller energy needs, to the consumption level of standard control/motion units, or even exhaustion systems. In such a scenario of no predominant contributor, and targeting to maximize energy efficiency, all sub-systems apart from the Laser unit must be accurately specified.

4. Best practices and improvement opportunities

Although energy efficiency improvements adopted along the last 20 years were seen to reduce energy requirements of machine-tools in approximately 50%, the basic guidelines for energy savings during process, such as the specification of most energy efficient

components and guidelines for effective energy management during machine-tool processing are still not established. The examples given in the previous section support the two strategies generally proposed to improve energy efficiency: (1) the conversion of hydraulic to all electric systems and (2) the maximization of the rate at which the physical mechanism can perform the desired operation, i.e., the optimization of machine usage.

It must be noted that awareness of the manufacturing end-user regarding the importance of energy management should be strongly enhanced. Although widely discussed in different areas, this is a topic that the manufacturing user tends to neglect, regarding each individual machine on his plant, particularly in what concerns technology, process and usage strategies. Independently on the many possible solutions targeting the automatic control of the machine-tool, the user's perception surely determines this optimization. Enabling the user to obtain detailed and real-time data about the energy consumption of the manufacturing process is essential to accomplish the optimization of the machine-tool environmental profile during the use stage, as the user must be actively involved in this process. It is on the side of the machine-tool manufacturer to preview and implement this. On the other hand, and apart from all criteria behind the selection of each individual sub-system on the machine, including its technology, it is on the manufacturer side to match the power demand profile of the main energy-consuming sub-systems integrated, in what concerns the power consumption of the sub-systems, as realised from the Laser cutting study followed.

However, as referred at start, the technology-related improvement potential of a manufacturing process towards benign metal forming must be sustained by an integrated perspective, mainly presenting energy-related technical solutions but not-only, as the contribution of the 3 types of resources listed above is affected, namely the assembly resources, the energy consumption during use and the other consumables related to machine operation, such as the influence of the hydraulic oil to the environmental impact of the bending process, as here demonstrated. Combining these perspectives, and in view of the discussed influence of the machine-tool technology on the environmental impact of the manufacturing process, special attention is here given to the assembled sub-systems of the machine-tool, and particularly to the materials incorporated on these, in which steel has traditionally been dominating. On the other hand, the change in steel pricing policy and current increasing steel cost are pressing overheads and margins at the machine-tools manufacturers and their components suppliers. As the need for alternative materials, less subjected to such market variations, becomes more evident, technical targets, process quality and environmental profile might be compromised. In addition, market has been specifically requiring performance increase, in the sense of higher stiffness, dimensional stability, ease of manufacturing, good dampening properties and high mass to avoid rigid body movements. Some examples of high potential actions enhancing benign metal forming currently being developed and adopted are pointed out in the next sub-sections.

4.1. Detailed analysis of assembled sub-systems components

Regarding the assembled sub-systems of the machine-tool, and considering the trend for all electric or electromagnetic versions of these, particular attention should be given to the use of advanced functional materials, particularly composites, and the increased use of additional electronic components, as these typically includes higher amounts of hazardous materials or raw materials which are hard to recover. Also on this analysis, the sub-system approach for improvement is recommended in order to favour a finer analysis of all components. In fact, while the significant impact of a housing material can be more evident from the volumetric contribution of the component, only a detailed sub-system analysis can insure that the determinant impact of a small volume component based on a hazardous material would not be missed. Although some mandatory related legislation is established for electronic components, the amount and combination of substances in a multi-component electromechanical sub-system is still relying on the environmentally conscious of the sub-system manufacturer.

4.2. Mass reduction of moving parts

In moving sub-systems/parts of machine-tools, the current replacement of standard materials by lightweight alternative materials simultaneously reflects the trend to optimized material consumption, general material reduction and the introduction of high-performance materials, such as reinforced polymer-based composites or low-density metals. Although this trend is often pointed out as a positive factor pushing for new dynamics to the sector, the issue of the environmental cost of the introduction of these alternative materials should be carefully analysed, particularly regarding the lifetime and end-of-life disposition of such components/materials, although a lot of work is on-going regarding innovative end-of-life strategies for these materials.

4.3. Mass reduction of structural parts

In what concerns the assembly resources used for the machine-tool construction, the materials and process inputs associated with the base structure of the equipment tends to determine its environmental impact, due to its dominant volume and weight. When looking for high performance materials for high-accuracy processes/systems, innovative polymer concrete solutions, also referred as mineral casting, are being introduced to replace the typical steel welded main structure towards a performance upgrade even in the most conventional machine-tools. Technically, this solution is indicated to overcome the static and dynamic stiffness and vibration damping requirements (Erbe et al., 2008), reflected on Figure 5, but, indirectly, this has significant environmental, technical and cost benefits.

Polymer concrete compositions mainly integrate a set of mineral granulates dispersed in a polymer resin. Granulates are abundant and several companies even supply these mineral products with certified composition, granulometry and general quality specifications, which have the advantage of being market proven, reducing risk and time-to-market. Unfortunately, although they are about 90% of the total weight of the composition, these components

represent less than 20% of the cost. In fact, polymer resins are the cost-drivers in these compositions. In general, epoxy resins are about four times more expensive than alternative polyester resins. Depending on the quality requirements, polyester could be a preferable choice, but they are less stable and present a higher shrinkage rate, which might be a problem in thicker bodies, as high shrinkage might result on significant internal stressing and subsequent cracking. Mineral casted structures can be produced in a single-step, and process time is mainly affected by the curing process, which depends mostly on the polymer characteristics (some products are presenting curing times up to 24 hrs at room temperature).

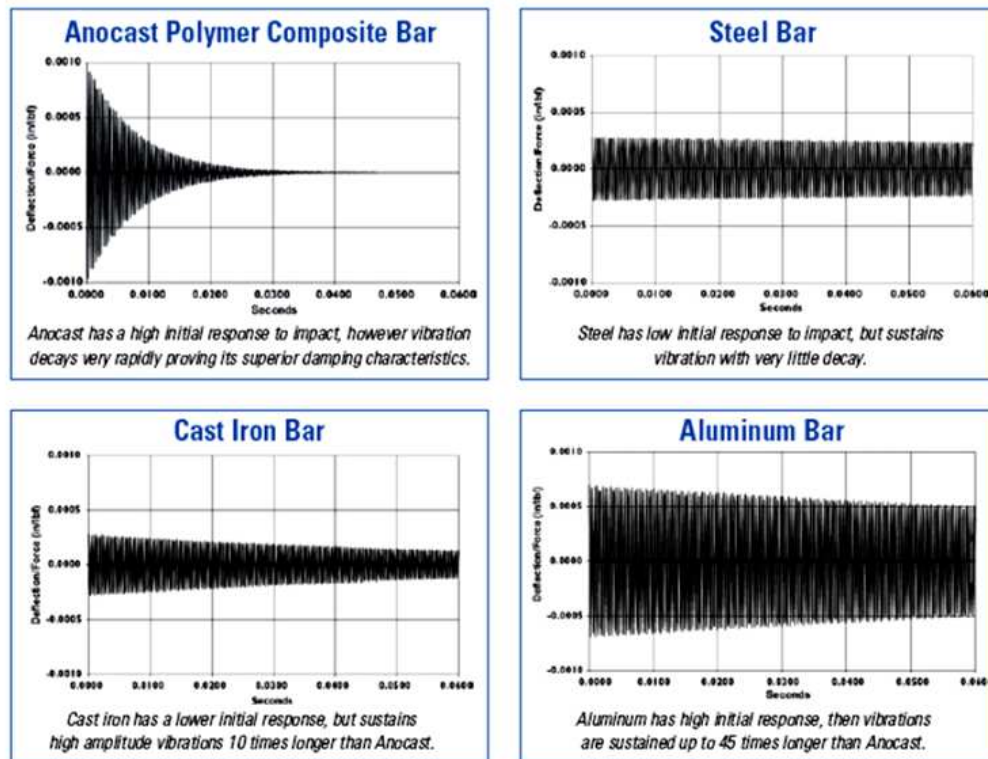


Figure 5. Comparative analysis of vibration dampening between conventional metals used in machine-tools and a commercially available polymer composite (based on Anocast product, a Rockwell Automation product (Rockwell, 2012)).

In turn, regarding the environmental benefits related to the introduction of polymer concrete-based solutions, the following aspects are to be highlighted:

- Reduction of process lead-time: Mostly depending on mixing, casting and curing processes, mineral cast structures are substantially faster available than the traditional casting or welded steel parts;
- Reduction of energy consumption during assembly phase of the machine-tool: The energy requirements to produce a polymer concrete structure is foreseen to be about 25% of that needed to produce an equivalent welded steel structure;
- Lifetime and potential for reuse: Mineral casting is chemically inert against aggressive materials such as oils, caustic solutions, acids and liquid-coolants. If crushed, it can be re-used as filler to the new mineral casting composition.

4.4. Selection of sub-systems technology and power matching

As concluded from the study on Laser cutting, although the sub-systems dimensioning and energy-consumption could be individually optimized for a specific range according to the application conditions, these are quite technology dependent. Besides, considering that one same machine-tool model typically operates in very distinct operating modes, it is important to insure that all sub-systems are properly synchronized in each operating condition, and the respective power-consumption profiles should be matched. This is expected to contribute significantly for the reduction on the power demand and improved efficiency of auxiliary main-systems against the main energy-source sub-system.

Besides the evidences coming from the laser case analysed, the impact of the motor power to the SPE values of the bending case also reflects some needs for improvement. Although the energy models presented are able to be tuned for different motor rated power levels integrated in press-brakes of different maximum bending capacity, this is indirectly associated to the maximum loading capacity of the machine. Obviously, in order to minimize power consumption, the motor rated power installed should be as low as possible, as made evident when comparing hydraulic systems (Table 1), where the lower motor rated power of the former resulted in over 49% energy savings when comparing a 110 t equipment with that of a 170 t equivalent. Moreover, in these hydraulic systems, where the stand-by consumption contributes significantly to the SPE, the motor power related energy savings are maximized with the increase on system usage.

5. Conclusion

The environmental impact of a manufacturing process is strongly determined by the basic features associated to the characteristics of the machine-tool selected to execute the process. The analysis of the machine-tool assembly is supported by the inventory of all substances used as components' materials or production consumables. In addition, the analysis of a specific manufacturing process corresponds to the collection of all substances used during utilization of the machine. In a full LCA of the machine-tool, this would correspond to the use-phase of the machine-tool life-cycle.

Machine-tool technology is the factor determining the assembly components type, amount and arrangement, and consequently the energy consumption profile of the machine, which rules the environmental performance of the manufacturing process. Modelling the energy consumption of a process firstly requires an adequate process categorization based on the technology of the main functional sub-systems. Other categorization criteria, such as the utilization mode, are also interesting, but more extensive work is needed to validate and reveal the most relevant sub-categories and associated environmental features. Attention should also be paid to the exergy reference unit used to define the specific process energy indicator. In the case of pure metal forming processes, which includes a set of chipless-shaping processes, some applying only discrete loads, typical units based on the amount of material removed are not appropriate. In such cases alternative units can be introduced, such as the energy per bending cycle proposed for bending.

In the future, the environmental impact of the manufacturing processes will be strongly affected by the trend for sub-systems modularisation, higher accuracy and versatility, as well as legislation and cost factors. The particular optimisation of the energy consumption of the machine-tools during process will require a strong awareness of machine-tool manufacturers and end-users, as the continuous improvement will not depend on a single measure. Proposed measures to be combined include solutions of alternative materials, either for small components or main structures, moving or structural parts, matching of sub-systems power profile and conditions of application, operating modes, maintenance needs and process chain shortening. Many high potential measures towards metal forming, and general manufacturing processes, are being revealed by dedicated groups, but extended work focused on the development and standardization of accounting and assessment methods customized for the purpose of evaluating the environmental profile of each manufacturing process category must be followed.

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