Estimation of laser cutting process efficiency

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Abstract. The efficiency of laser cutting processes is generally treated in technical literature in qualitative terms, referring to ways to increase it. The present paper is focussed on metal cutting by laser and proposes some quantitative means to estimate the process efficiency. For certain working conditions – machine-tool, material to be processed, specific costs and other – the effectiveness and the specific power consumption are computed based on the main cutting parameters: laser power and cutting speed. The proposed mathematical relationship can be successfully used when the criterion of process optimization is the environment friendliness. A relevant case study is presented, as well. When significant different samples are to be compared, the criterion used to evaluate laser cutting efficiency becomes very important.

1. Introduction
Generally speaking, efficiency of machining processes is a relative vague concept. It can be interpreted in terms of economical or technical aspects, it can refer to different specific processes, or to a certain material. In the technical literature, the efficiency of machining processes is approached mainly from the perspective of the ways to increase it.

A survey of literature reveals different kinds of the concept’s approach. First of all, different materials processed by laser are studied in research works: metal, polymers, glass, textile, human tissue, ceramic and others. Thinking about the specific of laser processing, different types were found: cutting, remote cutting, laser-assisted machining. In terms of areas of applying laser processing, the main ones were industry and medicine. Indifferently the material, type of laser processing, or area of applying, the most frequent approach of efficiency’s study is dedicated to ways of improving it.

So that, in [1], are presented researches regarding the efficiency of the remote laser metal cutting. In context of the cited paper, authors mean by ‘efficiency’ the capability of an installation to cut an as possible thick steel plate. It was proved that a steel wall having the thickness of 60 mm can be cut with power of 7.5 kW of the laser radiation. In the paper [2] an optimization method of laser cutting parameters is presented. Rate of removal of the melted material by assistant gas was used as basis to define a model to estimate the cutting process. Though the title of [3] refers to the efficiency of laser cutting of electrodes for Li-Ion batteries, a main aspect treated is focused on physical phenomena encountered at this kind of processing. This paper presents the advantages of laser cutting of electrodes compared to classical machining, and the efficiency of the laser cutting is estimated in relationship with cutting parameters. The articles [4] and [5] discuss laser-assisted cutting, for that the laser is an auxiliary process that only assists mechanical cutting, making it more effective and accurate. The reference [4] presents the results of a combined process in which laser heats selectively the zone of glass to be cut, thus becoming easier machinable. The type of chip is modified, and the main consequence is a better geometrical accuracy and roughness of the part. The reference [5] presents a hybrid method to process materials: a classical machining preceded by a preheating by means of a laser beam. Neither the type of
cutting (milling, turning, other), nor the material are specified. The cutting parameters are selected in accordance with the modified properties of the material. It was proved that cutting combined with laser pre-heating was more effective and the dimensional accuracy and roughness were better compared to classical machining. Power consumption was reduced, as well. In [6] the efficiency of cutting textile materials is appreciated by means of percentage of laser power lost by the transluminate phenomenon. This loss is directly influenced by the angle of fibers. The paper [7] provides an overview on the impact on environment of laser cutting technologies. It is a discussion mostly in qualitative terms, with regard to the way to generate the beam. The recent advances in laser technologies provide industry with equipment more efficient in terms of power consumption. The main drawback of this equipment is that the quality of the machined surface quality is lower, especially for sheets with bigger thickness. In [8] a study on the efficiency of laser cutting of ceramics is presented. Ceramics machining has some specific features related to the need of high laser power, because of high temperature needed to cut such a material. In these conditions, the problem of efficiency becomes more relevant and cutting parameters have to be carefully selected to get a good quality of the product. Thermodynamic and efficiency analysis are combined in the research. The paper [9] presents the investigations which had as a goal finding the optimum in terms of requirement of specific energy to cut holes in Kevlar plates. The needs of specific energy is computed related to different scanning speed, laser power, and diameter of machined holes. The papers [10, 11] refer to using laser to work on human tissue, and present the problem from the perspective of cutting efficiency. In [10] efficiency is appreciated mainly in terms of the quality of the surface obtained. Talking about human tissue, an important aspect was the measure it was affected by processing, for instance if the dentine tubules were occluded or remained opened.

As it can be seen in the approaches presented above, none of the researches have put the efficiency of laser cut processing in a direct relationship with the cutting parameters. Furthermore, in some cited papers, efficiency expresses rather the capability of the process to produce some certain output, than its effectiveness. The present paper proposes a discussion on different ways to interpret efficiency as effectiveness, and how can it be directly, or indirectly influenced by the cutting parameters.

2. Efficiency indicators of laser cutting processes

To narrow down the area of research, and to be more specific, the present paper focusses on laser cutting of metal. For this particular category of materials, the process consist mainly of melting (and even vapouring) and removing the melt. The volume previously filled by the melt becomes the so called kerf that separates the part and the metal sheet. In this context, efficiency can be interpreted in different ways, or expressed by different indicators, as follows:

- **Effectiveness**, that is how fast a part is produced;
- **Linear specific energy** ($E_l$). This expresses one way to appreciate the measure the process is friendly to environment. This can be estimated by the quantity of energy spent to process a unit of length of part edge. Of course, the lower the linear specific energy is, the more environmentally friendly the process is considered to be;
- **Surface specific energy** ($E_s$). This indicator is intended to take into account the thickness of metal sheet. It expresses the energy spent to process a unit surface on the side of cut part;
- **Volume specific energy** ($E_v$). This is a third mean to appreciate the measure the process environmentally friendly. This can be estimated by the quantity of energy spent to melt a unit of volume, and is interpreted in the same way as the previously specified indicator.

These indicators are influenced by some input parameters as: laser power, cutting speed, pressure of the assistant gas, the processed material itself (characterized by different properties as specific heat, conductivity and other), the metal sheet thickness. It is important to note that these parameters influence directly by their values the efficiency indicators, but also indirectly, by means of their combined effect/interaction (especially the couple power-speed). The cutting parameters can be directly adjusted in the process, to influence in a direction or in the opposite one any efficiency indicators. Some other data are given, and cannot be changed for a specific batch, e.g. the part material itself or the thickness of the metal sheet. This is the reason for that the given data will not be involved in computing efficiency indicators. Discussions on each of the mentioned indicators are provided in the following paragraphs.
2.1. Effectiveness
Effectiveness is already used as an indicator to express efficiency. It is easy to be computed, based only on cutting speed and the length of the part contour. Obviously, the higher the cutting speed is, the efficiency is better. It has to be mentioned, that this is a rough indicator, used mainly when the target is minimizing cutting time. Furthermore, changing cutting speed should be accompanied by an adjustment of laser power that produces some side consequences that cannot be appreciated exclusively by this indicator.

2.2. Linear specific energy
Linear specific energy ($E_l$) measures the quantity of energy spent to process a unit length [mm] of part edge. This depends on the power of laser, and the time spent to process 1 mm of part edge (3).

$$E_l = \frac{P \times t}{L}$$

(1)

$$t = \frac{L}{v}$$

(2)

$$E_l = \frac{P}{v}$$

(3)

In (1), (2), (3) we have:

$E_l$ – Linear specific energy [W*s/mm], [J/mm];

$P$ – Laser power [W];

$t$ – Processing time [s];

$L$ – Length of part side edge (contour) [mm];

$v$ – Cutting speed [mm/s]. Note that in the context of NC (Numerically Controlled) machine-tools the usual unit measure for speed is [mm/min], so the appropriate transformation to [mm/s] should be performed before using the value in formula.

Replacing (2) in (1), easily results (3), the linear specific energy $E_l$.

This is a synthetic indicator, since it does not take into account thickness of the part, or other input data. It can be used to appreciate the efficiency of the cut within a certain batch, where thickness is a given data and cannot be modified, hence, has to be not involved in any computing relationship. According to (3), a process is more efficient if ratio $P/v$ has lower value. Though, specific technological restrictions do not allow decreasing laser power below a certain limit, on one hand, and equipment limitations restrict increasing cutting speed over a limit, on another hand. Furthermore, the combined action of power and speed force user to adjust the mentioned ratio in a reasonable range. With all these, $E_l$ still remains a useful indicator to appreciate cutting efficiency in terms of eco-friendly technology criteria, and guides user to adjust cutting parameters towards the goal of saving energy.

2.3. Surface specific energy
Surface specific energy ($E_s$) is already used as an efficiency indicator by some authors [11,12]. Such an approach takes into account the thickness of the part, to calculate the energy spent to process a unit of side surface of the part (6) [11,12]. Similar relationships are often used to describe the specific energy consumption expressed by how large side surface can be processed spending a unit of energy.

$$E_s = \frac{(P \times t)}{A}$$

(4)

$$t = \frac{L}{v}; A = L \times h$$

(5)

$$E_s = \frac{P}{v \times h}$$

(6)

where:

$E_s$ – Surface specific energy [W/mm²];

$A$ – Side surface area of the part [mm²];

$h$ – Metal sheet thickness [mm].

Anyway, such a comparison should be performed with a grain of salt, especially when the difference of thickness is big. In such a situation the physical phenomena that is developed during cutting might differ significantly (at least in their magnitude) and alter the result of comparison. When it comes to apply it for practical purposes, it allows to compare processing parts having different thicknesses in terms of efficiency in respect to environment protection.
2.4. Volume specific energy

Volume specific energy ($E_v$) is an indicator that shows how much energy has to be spent to melt a unit volume of material. It takes into account the average width of kerf (9). In a derivate shape, some authors name it melting efficiency [11].

$$E_v = \frac{(P \cdot t)}{V}$$  \hspace{1cm} (7)

$$t = \frac{L}{v}; \hspace{1cm} V = \frac{L \cdot A_k}{P}$$  \hspace{1cm} (8)

$$E_v = \frac{\nu \cdot W_{avg} \cdot h}{v}$$  \hspace{1cm} (9)

where:

$E_v$ – Volume specific energy [W/mm³];
$V$ – Volume of kerf (of melt material [mm³];
$S_k$ – Area of cross section of kerf [mm²];
$W_{avg}$ – Average kerf width [mm] (according to figure 1).

We consider that the relationship (9) is important because depending on input variable parameters: laser power and cutting speed, on one hand, pressure of assistant gas and even focus point and given properties of the material (specific heat, conductivity, reflexivity) on other hand, the shape and width of kerf (gap between the part and raw material) varies. This variation, can be sometimes relatively significant, but it does not influence the part itself if trajectory corrections are correctly applied. The wider the gap is, a bigger volume of material have to be melted. In these terms, the less quantity of material to be melt (that is the narrower kerf) is advantageous in terms of energy consumption.

3. Case study

3.1. Case study setup

A case study was conducted to illustrate using the indicators of laser cutting processes efficiency. Hardox 400 and Hardox 450 steels have been cut with different combinations of input data. Hardox is difficult to be machined alloy and it is often processed by means of non-conventional methods, as abrasive waterjet [13] or laser cutting. Combinations of laser power ($P$) and cutting speed ($v$) levels were selected from data sets, according to design of experiments (DOE) procedures. For the case study presented here, the trial values of $P$ and $v$ are displayed in table 1, along with other variable input data as the steel sheet’s thickness and the average width of the kerf. Note that the average width of the kerf is considered an input data for this case study. In fact, it was measured for each part; its value is influenced by the value of $P$ and $v$, and their combined action on the metal sheet, as well. The combinations used limit values for $P$ and $v$, which were determined by means of initial test screening trials, as to be sure that cutting process develops properly, that means that the part is completely cut (separated from the sheet material) and the machined surface’s roughness is appropriate. Even if the combinations where the extreme low, or extreme high values for both the input parameters were coupled, the part output quality was acceptable.

All the tests were performed for the same shape of part, formed of three segments and an arc. The length of contour was $L = 91.4$ mm.
The specific energy in its different forms was computed for each combination and the output data were centralized in table 2. The link between table 1 and table 2 is done by means of number of test (column Test#).

| Test# | Material  | Power \( P \) [w] | Cutting speed \( v \) [mm/min] | Sheet thickness \( h \) [mm] | Average width of kerf, \( W_{avg} \) [mm] |
|-------|-----------|-------------------|------------------|----------------|------------------|
| 1     | Hardox 400 | 4100              | 1200              | 10             | 1.285             |
| 2     | Hardox 400 | 4100              | 1600              | 10             | 1.105             |
| 3     | Hardox 400 | 4200              | 1600              | 10             | 1.470             |
| 4     | Hardox 400 | 4200              | 1200              | 10             | 1.090             |
| 5     | Hardox 400 | 4300              | 1600              | 10             | 1.190             |
| 6     | Hardox 400 | 4300              | 1200              | 10             | 1.135             |
| 7     | Hardox 450 | 3700              | 1450              | 12             | 0.610             |
| 8     | Hardox 450 | 3700              | 1650              | 12             | 0.870             |
| 9     | Hardox 450 | 3800              | 1450              | 12             | 0.890             |
| 10    | Hardox 450 | 3800              | 1650              | 12             | 0.610             |
| 11    | Hardox 450 | 3900              | 1450              | 12             | 1.060             |
| 12    | Hardox 450 | 3900              | 1650              | 12             | 0.610             |

| Test# | \( E_l \) [J/mm] | \( E_s \) [J/mm^2] | \( E_v \) [J/mm^3] |
|-------|------------------|-------------------|-------------------|
| 1     | 205.000          | 20.500            | 15.953            |
| 2     | 153.750          | 15.375            | 13.914            |
| 3     | 157.500          | 15.750            | 10.714            |
| 4     | 210.000          | 21.000            | 19.266            |
| 5     | 161.250          | 16.125            | 13.550            |
| 6     | 215.000          | 21.500            | 18.943            |
| 7     | 153.103          | 12.759            | 20.916            |
| 8     | 134.545          | 11.212            | 12.887            |
| 9     | 157.241          | 13.103            | 14.723            |
| 10    | 138.182          | 11.515            | 18.877            |
| 11    | 161.379          | 13.448            | 12.687            |
| 12    | 141.818          | 11.818            | 19.374            |

| Test# | Rank | Criterion \( E_l \) | Test# | Rank | Criterion \( E_s \) | Test# | Rank | Criterion \( E_v \) |
|-------|------|---------------------|-------|------|---------------------|-------|------|---------------------|
| 1     | 8    | 8                   | 2     | 10   | 10                  | 11    | 11   | 11                  |
| 2     | 10   | 10                  | 3     | 12   | 12                  | 8     | 8    | 8                   |
| 3     | 12   | 12                  | 4     | 7    | 7                   | 5     | 5    | 5                   |
| 4     | 7    | 7                   | 5     | 2    | 2                   | 2     | 2    | 2                   |
| 5     | 2    | 2                   | 6     | 9    | 9                   | 9     | 9    | 9                   |
| 6     | 9    | 9                   | 7     | 3    | 3                   | 1     | 1    | 1                   |
| 7     | 3    | 3                   | 8     | 5    | 5                   | 10    | 10   | 10                  |
| 8     | 5    | 5                   | 9     | 11   | 11                  | 6     | 6    | 6                   |
| 9     | 11   | 11                  | 10    | 1    | 1                   | 4     | 4    | 4                   |
| 10    | 1    | 1                   | 11    | 4    | 4                   | 12    | 12   | 12                  |
| 11    | 4    | 4                   | 12    | 6    | 6                   | 7     | 7    | 7                   |
3.2. Discussions
As it can be observed relatively easily, the values of $P$ and $v$ for the two materials differ. As was previously stated, they were selected based on test processing performed to find the limit values for which cutting still develops properly. Values lower than the minimum ones, or higher than the maximum ones cause improper running of the process, with non-conform output parts. The different values for the two materials are imposed by the different thermal properties of the materials.

Observing the output data displayed in table 2, can be drawn several conclusions:
1. It is obvious that for both the materials, the linear specific energy $E_l$, that depends exclusive on $P$ and $v$, according to (3) the highest value of $E_l$ is recorded for the combination with lowest $P$ and highest $v$; the difference in terms of $E_l$ value between the two materials is given by their different properties.
2. The influence of $h$ on surface specific energy $E_s$, shows that this indicator becomes more useful when it is to compare in terms of cutting efficiency related to environment protection parts made of different materials and having different thickness. In these conditions, parts made of Hardox 450, that is those having a bigger thickness are placed at the top of the list, the first four having been ranked the same as according to criterion $E_l$.
3. Criterion based on volume specific energy $E_v$, comes with some apparently random results. Being involved more input data, it is almost impossible to appreciate without this indicator which is the least and most energy consuming sample. According to this criterion, the best combination is #3: Hardox 400, thickness of 10 mm, laser power of 4200 (medium), and cutting speed of 1600 mm/min (the highest). The worst sample (the most energy consumer per melted volume unit) is Hardox 450, thickness of 12 mm, laser power of 3700 (the lowest), and cutting speed of 1450 (the lowest). In this context, referring to lowest and highest value of a parameter we mean the extreme value used for a certain material. This is an important remark, because from technological reasons, different minimum-maximum $P$ and $v$ values must be set up for different materials, depending on their physical properties.
4. Table 3 provides a good imagine of ranking the samples according to different criterion, all of these being related to eco-friendly technologies. Values in columns 2, 3, and 4 indicate the number of sample placed on rank stated in column Ranking.
5. It is important to select correctly the indicator used to appreciate a certain case (set of part samples), according to the input variable data that can be controlled. We have to keep in mind that in certain cases, some input data could be fixed, they may not be changed (e. g. material, or thickness of the part).
6. Depending on the appreciation criterion ranking may differ, sometimes drastically, as can be seen in table 3 and depicted in figure 2.

4. Conclusions
Nowadays, when environment protection becomes a stringent problem, taking care about energy consumption is an important task. In this context, the energy consumption becomes an important criterion of optimization in manufacturing. Of course, the technical/technological criterion remains the most important, but the environment protection cannot be neglected anymore. The research presented here has proved that even respecting the technological restrictions, that is obtaining parts conform to specifications, still optimization in terms of energy consumption can be performed. The task is not easy, because of the many input data involved and of the particularities specific to each application apart. A mean to appreciate the efficiency of laser cutting of metals are the efficiency indicators, which have to be selected correctly, according to the specific available input data.
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