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THE ENVIRONMENTAL IMPACT PRELIMINARY STUDY OF MANUFACTURING MACHINING BY APPLYING CO_2PE METHODOLOGY

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ABSTRACT: The paper main aim is to document and analyze the environmental impact of some machine tools working phase, as well as to identify potential for environmental improvement. The work focuses on two case studies, one for conventional machining, e.g. milling machining and the other one for a nonconventional machining, e.g. electrical discharge machining (EDM), using CO_2PE! methodology. This comprises two approaches, the screening one, which provides a first insight into the unit process and in-depth one, in which all relevant process inputs and outputs are measured and analyzed in detail.

KEY WORDS: CO_2PE methodology, Environmental impact, Manufacturing Processes

1. INTRODUCTION

Machine tools sector is one of the most important in Europe concerning GDP (180 billion € of new orders before the crisis, 74 billion €/year in Q2 2010). The market segment is composed mainly by SMEs; as users: 99.7% by number, 78.2% by GDP, 82.8 by employed persons; as machine manufacturers: 98.7% by number, 49.7 by GDP, 56.5 by employed persons [1]. In the same context, the relevance of the sector concerning energy consumption is high (>10,000 PJ/year) and therefore the financial pressure is high due to unbalanced demand/offer of energy due to energy price increase (as in 2007-2008). But recent developments in manufacturing technologies have provided machines and processes of higher performance and energy use, aiming at enhance of productivity and reliability of the machining [1].

Taking into account the data mentioned above, the constraint for increased productivity with decreased production cost is critical. Furthermore, the environmental awareness of people has led to legislative stress, substantiated in EuP Directive. So, in the close future, it is very probable that machine tools will experience some energy efficiency regulation and classification in this respect [2].

It is considered that manufacturing processes are answerable for a significant part of the environmental impact of products but so far, they are defectively documented in terms of their environmental trace [3].

Manufacturing processes were the topics of intense discussions concerning energy efficiency as result of the energy cost increase and the associated green house gas emissions [4].

In this respect, some preliminary environmental studies regarding material removal processes carried on by machine tools like turning, milling etc. indicated that more than 99% of the environmental impacts due to the electrical energy consume [5].

In this context, the CO_2PE! - Cooperative Effort on Process Emissions in Manufacturing Initiative has been launched in 2009. This initiative has main objective to coordinate international efforts in order to document and analyze the global environmental impact for an extensive range of accessible and rising manufacturing processes concerning their direct and indirect emissions and to provide guiding principles to improve these items [6].

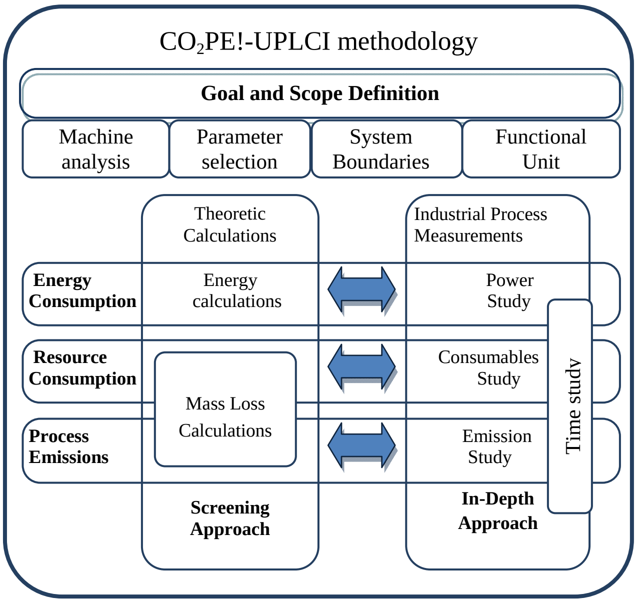

Figure 1. CO_2PE! Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory [7]

In the frame of CO_2PE! methodology, two approaches are considered: screening approach and in-depth approach, summarized in figure 1.

2. THEORETICAL PHASE

The screening approach is illustrated by means of two case studies, a conventional machining (milling), and a nonconventional machining (electrical discharge machining).

2.1 Milling process

Commonly, turning and milling are the most extensively applied material removal processes in manufacturing. Several modes to compute the consumed energy to remove the material through milling were reported in the state of art.

The theoretical energy for subtractive processes through machining is equal to the amount of work required to remove the material, which is mainly composed by the shear and friction energies. On this basis, theoretical energy e_{th} can be calculated with the following relation [9]:

$$e_{th} = e_s + e_f = \tau\gamma + \left(\frac{F_c r}{bt}\right) \text{ [J/cm}^3\text{]} \qquad (1)$$

where e_s is the specific shear energy [J/cm^3] and e_f - the specific friction energy [J/cm^3]; τ and γ are the shear strength and shear strain [MPa]; F_c - the cutting force component parallel to the tool face [N]; r is the cutting ratio; b and t are the cut depth [mm] and feed[mm/rev], respectively. The shear energy during cutting represents approximately 65-80% of the total specific energy.

From another point of view, the shear energy is defined as a function of the Brinell hardness (HB) of the material [10]:

$$e_s \left[\frac{KJ}{cm^3}\right] = (0.005 - 0.01)HB \quad . \qquad (2)$$

Thus, the theoretical specific energy for carbon steel with a Brinell hardness of 200 results 246 KJ/Kg, taking also into account the steel density.

The electrical energy needed for milling process using the screening approach was determined. Thus, the specific energy consumption e_{sc} consists of three parts: the cutting energy, the idle energy (all systems active but no effective cutting and excluding the basic energy) and the basic energy (auxiliary systems running, no active positioning or cutting). This is calculated with the following relation [11]:

$$e_{sc} = e_p + \left(\frac{P_{idle}}{MRR}\right) + \left(\frac{P_{basic}}{MRR}\right)\left(1 + \frac{t_s}{t_m}\right) \text{ [J/mm}^3\text{]} \quad (3)$$

where e_p is the specific cutting energy [J/mm^3]; MRR - the material removal rate [mm^3/s] ; t_s and t_m - the standby and machining time; P_{idle} and P_{basic} - the average power consumption levels for idle and basic modes.

These energy consumption models suggest that at higher MRR, it results less energy consumption for removing same volume of material. Especially, when MRR is increasing from less than 1 cm^3/s to more than 1 cm^3/s, the energy saving is significant [5].

2.2. Electrical discharge machining process

EDM is the best known for its ability to precisely machine complex shapes in very hard metals due to its very well controlled thermal- based material removal. EDM has earned sustainable position along with milling and grinding equipment as a proactive, mainstream technology [12].

The main influence in terms of environmental impact in EDM was determined by studying electrical parameters such as current, pulse duration and voltage, and material properties of workpiece and electrode, like the material's melting temperature, as well as its electrical and thermal conductivity [13].

In this frame, at EDM process, the energy distribution for 1 hour of EDM roughing (copper electrode, hard metal workpiece) was determined and is presented in figure 2.

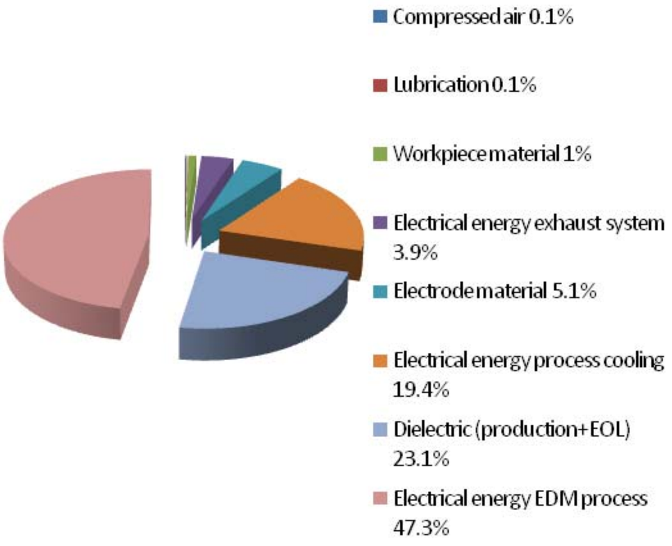

Figure 2. Distribution of the environmental impact for 1 hour of EDM roughing (copper electrode, hard metal workpiece) [6]

For die sinking EDM a time study was performed for ten different product designs on four different machine tools during six days [3].

Thus, three used working modes have been identified as: standby mode (e.g. process waiting for operator), supporting tasks mode (e.g. workpiece clamping, tool change, calibration) and the operational mode (e.g. material removal). Figure 3 shows the share of these mentioned above working modes.

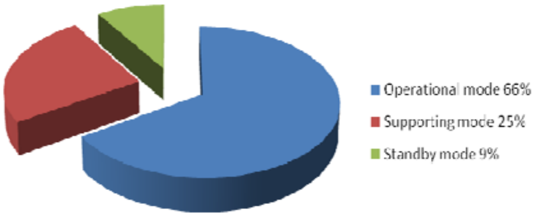

Figure 3. Time share of the different EDM working modes [3]

From the data presented above, an important amount of energy can be saved with a significant environmental impact. That consists in reducing the supporting time of any process of material removal, by reducing the auxiliary times, through using on large scale, the high speed automatic tool change, and workpiece. This remains an open challenge for machine tools manufacturers to reduce auxiliary times even in case of low series of fabrication or unique products. Nowadays, this production type becomes more and more important due to major trend of customer tailored-made products.

3. EXPERIMENTAL APPROACH

3.1.General processes information

The objective of the study is to comparatively analyze the energy consumption for the same amount of removed material, using screening approach of CO_2PE methodology, for a conventional machining, respectively milling and for a non-conventional machining - EDM.

The work piece material is 1.2343 (equivalent to X37CrMoV5-1, according to EN ISO 4957:2000) hot-work tool steel with the chemical composition presented in table 1.

Table 1. Chemical composition of material (%)

C	Si	Mn	P	S	Cr	Mo	V
0.33 - 0.41	0.8 - 1.2	0.25 - 0.5	max 0.03	max 0.02	4.8 - 5.5	1.1 - 1.5	0.3 - 0.5

The workpiece has undergone a vacuum quenching process and its Rockwell hardness was determined, of around 45 HRC. The workpiece is a block with dimensions 45×45×30 mm (L×W×H) which was the subject of the two machining processes, in which a pocket was obtained with dimensions: 10 mm depth, 20 mm length, 10 mm width, 5 mm radius, and the shape shown in figure 4.

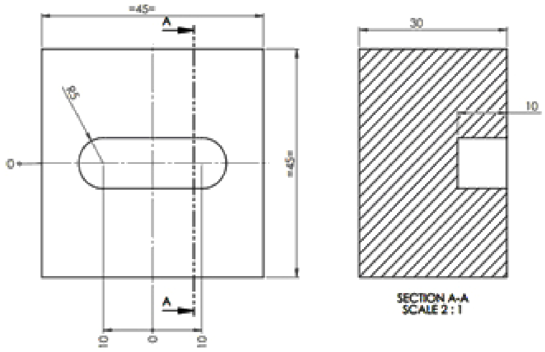

Figure 4. Workpiece shape

3.1. Milling process

Milling process was achieved on a five axis CNC vertical machining center with 18,000 rpm spindle speed, Deckel Maho U 50.

The Inova milling cutter from titanized metallic carbide had 6 mm diameter and is presented in figure 5.

Figure 5. The cutter used in milling experiment

An image taken during machining process is presented in fig. 6:

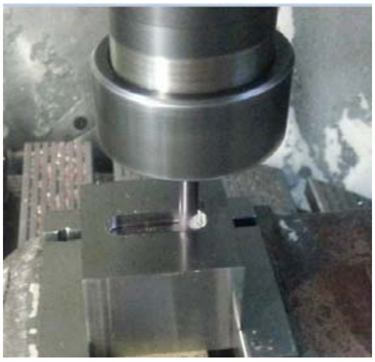

Figure 6. Milling process of cavity

The adopted milling strategy was a pendular one (fig. 5), concerning, sweeping all cavity surfaces, taking into account that picked tool diameter is lower than lowest cavity transversal dimension.

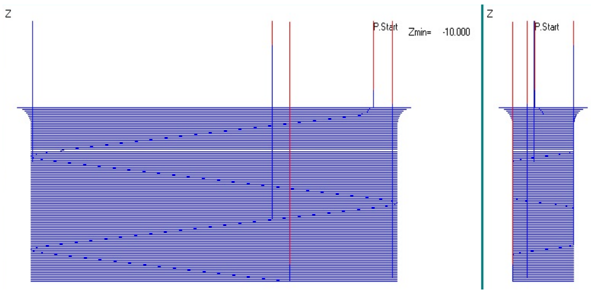

Figure 7. Adopted milling strategy

This strategy aims at effective power decrease – the average power consumed for machining was evaluated in-situ at around P_m = 2.5 kW – and to reduce the machined surface roughness.

The used cutting parameters were: feed - 800 mm/min, and main spindle speed - 4000 rev/min.

The machined surface obtained by mentioned above milling parameters, had a surface roughness evaluated at around Ra=3.2 μm, shown in fig. 8:

Figure 8. Cavity shape obtained through milling

The estimation of specific energy used to material removal during above depicted process was achieved using the following relations.

The consumed energy was determined:

$$e_c = P_m \cdot t_m \qquad [\mathrm{J}] \qquad (4)$$

where: P_m is estimated consumed power at milling; t_m – machining time, which was 10 min in this particular case. Therefore, the consumed energy was e_c =1500 J.

The specific energy (e_s), consumed for removal of volume unit was determined with the relation:

$$e_s = e_c / V_r \quad [\mathrm{J}] \qquad (5)$$

where V_r is the volume of removed material, i.e. the volume of machined cavity, which is calculated from the data presented in fig. 3, V_r = 2.785 cm^3. Hence, e_s = 538.6 J/ cm^3.

3.2. EDM process

Die sinking electrical discharge machining was accomplished on a SODICK AQ55L, using a cooper electrode, with the frontal surface area of 278.53 mm^2, clamped with a EROWA device, as it is shown in fig. 9. The main working parameters used under positive polarity are presented in table 2:

Table 2. EDM working parameters

Parameters	Value	MU
Peak step current, i_p	6.5	A
Pulse time, t_{on}	190	μs
Pause time, t_{off}	40	μs
Discharge tension, u	20	V

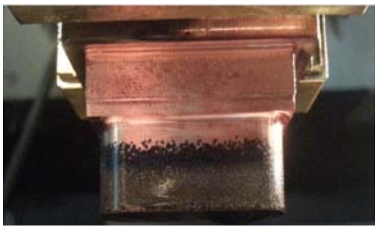

Figure 9. Cooper profiled electrode used in experiment

An image taken during EDM test, whose machining time was t_{EDM}=110 min, is presented in fig. 10:

Figure 10. EDM process of cavity

The obtained machining surface with a similar roughness to that obtained at milling, i.e. Ra=3.2 μm on lateral surface, is presented in fig. 11.

Figure 11. Cavity shape obtained through EDM

The discharge energy (e_d) was determined based on relation [11]:

$$e_d = \int_0^{t_{on}} i(t)u(t)dt \qquad [\mathrm{J}] \qquad (6)$$

The data from the table 2 led to e_d =0,247 mJ.

In order to estimate the consumed energy during machining time, it is critical to approximate the number of normal discharge produced (with the energy calculated above), which, under usual EDM stability, could be around k_n=90% from the total number of discharges occurred; the rest is considered idle.

Therefore, the number of normal discharges (N_d) occurred during machining time, could be estimated with the relation:

$$N_d = \frac{t_{EDM} \cdot 60}{t_{on} + t_{off} + t_d} k_n \qquad (7)$$

where t_{EDM} is machining time [s]; t_{on} - pulse time [s]; t_{off} – pause time [s]; t_d - delay time [s], which, in this case, was estimated as an average of 10^{-5} s.

Hence, it results an estimated number N_d=2.48 10^7.

The consumed energy during machining time was estimated with the relation:

$$e_c = N_d \cdot e_d \qquad [\mathrm{J}] \qquad (8),$$

resulting, $e_c=6.11 \cdot 10^5$ J.

The consumed power during machining was:

$$P_m = e_c / t_{EDM} \quad [W] \qquad (9),$$

resulting, $P_m = 92.62$ W.

Therefore, the specific energy, on volume unit of removed material was:

$$e_s = e_c / V_r = 2.2 \cdot 10^2 \text{ kJ/cm}^3.$$

4. CONCLUSIONS

The data offered by our theoretical approach underlined the importance of auxiliary time decrease even in case of small series and unique production, the actual major trend in manufacturing, in order to reduce environmental impact in terms of consumed energy.

The results provided by our experimental approach emphasized that consumed power at EDM during machining was lower than in case of milling the same cavity surface. This could be obviously correlated with huge differences in terms of machining rate of those analyzed machining types. Regarding specific energy, the energy consumed on volume unit of removed material, an expected difference was noticed of 10^2 order of magnitude. Even this screening approach shows a net superiority of milling comparing to EDM regarding environmental impact due to specific energetic consume, EDM is still indispensable in the context of major trend of new materials emerging, hard or impossible to conventionally machine. In the mean time, researches are carried on to reduce environmental impact of EDM by increase its machining rate, using aiding fields, like ultrasonic, magnetic, ultra-low temperature etc.

5. ACKNOWLEDGEMENTS

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