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Environmental impact reduction for a turning process: comparative analysis of lubrication and cutting inserts substitution strategies

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Abstract

Machine tools are responsible for a relevant share of environmental impact related to production processes. This is due to their widespread use, the huge energy requirements during operations and the disposable materials involved in the process like scraps, cutting inserts and exhausted oil. This study presents a holistic analysis of the main contributions that are responsible for the environmental impact of the process and the use of the analysis's results to optimize the process setup for a specific case. The factors included in the analysis are: cutting parameters, lubrication strategy and cutting inserts substitution. Regarding the cutting parameters choice, the analysis of the tests carried out highlighted that the best solution is to use the most demanding process parameters in terms of material removal rate, using the tool strength as a constraint. The comparison of alternative lubrication strategies shows the advantage of using dry machining, to be replaced with MQL only when hard-to-cut materials must be machined. Finally, the approach developed to assess the environmental footprint associated to the cutting inserts allowed to define a new substitution rule. The obtained solution is consistent with the usual industrial practice to change the tool when the geometrical tolerances could not be meet anymore, this result is due mainly to the high environmental impact of the production phase of the insert.

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Keywords: Green Manufacturing; Process Optimization; Turning; Lubrication; Cutting Insert Wear.

1. Introduction

New technologies are continuously presented on the market for the production of metal components, such as Additive Manufacturing, however metal cutting processes maintain their leading role within the production processes due the high achievable tolerances and high surface finish that only such processes could obtain. In the last decades, machine tool manufacturers have developed solutions to improve their machines' performances in order to increase the material removal rate and process accuracy and precision. This has led to the introduction of new cutting materials and higher performance motors and controllers. One of arising challenges is now to achieve a process as sustainable as possible. For the assessment of sustainability, it is necessary to consider not only the environmental impact of the process but also the economic sustainability for the user (process cost and revenues). The importance of developing green and sustainable processes has been initially introduced by Donnelly et al. [1] and Wienert et al. [2] that proposed a metric to evaluate the environmental impact, Sutherland et al. [3] that studied the effect of lubrication while Rangarajan and Dornfeld [4] focused on different strategies to measure and reduce the energy consumption. From these contributions emerges that to assess the sustainability of a machining process, it is necessary to adopt a holistic approach able to include in the analysis the contributions of different factors. The main feasible actions that must be taken into account when optimizing a machining process are related to: the process parameters choice [5], the lubrication strategy

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selection [3], and geometrical consideration that could reduce the axis movements like the workpiece orientation and positioning on the machine's table [6,7]. This paper is focused on one of the most common machining process: turning.

The first step for the optimization of the process is the analysis of the energy consumption during the machining process. Machine tools, like lathes, have a share of energy needed by the spindle that is usually lower than the one needed by the support systems. Moreover, this is speed dependent, as reported by Rajemi et al. [10], where it is highlighted for a MHP CNC lathe machine that the power needed for cutting ranges from 31% to 39% depending on the cutting speed. Different authors report also how the increase of complexity of the machine affects the electrical power consumption [11]. As stated by many authors, the power consumption could be reduced thanks to the optimal choice of process parameters [5,12,13] and thanks to the introduction of innovative design criteria for modern machine tools, with special care to the power management during the not cutting states of the machine [14].

However, when implementing a holistic analysis of the process is mandatory to include into the analysis also other parameters that affect not only the power consumption but, in general, the environmental impact of the process. Considering the environmental footprint of machining, many studies have been carried out on lubrication selection. The reason that leads to focus the attention on lubrication is twofold: the use of lubrication has a huge environmental impact and its cost is very high, especially for hard-to-machine materials. Moreover, lubrication affects the global process performance: mainly tool wear and surface finish. An example of the importance of the use of lubricant is provided by the study of the Japanese market where lubricants consumption and costs have been recorded [8]. Other authors [9] provided also an estimation for the percentage of manufacturing cost due to lubrication, this value range from 7% to 17%, higher when the materials are difficult to cut. However, this is not the only contribution to be included for the process optimization. To have a holistic view also the effect of process parameters on power consumption and cutting inserts substitution will be taken into account.

At the end, also the use of disposable materials must be taken into account. For a turning process this include mainly the cutting inserts. Cutting inserts are really critical from an environmental point of view since the materials actually used to produce such inserts are energy intensive. A change in the substitution rule of the cutting inserts based on their environmental impact is interesting from an industrial point of view because such solution does not require dramatic changes in the production process, differently from other approaches like the introduction of a new lubrication system. To define an optimal substitution strategy is necessary to create a model to assess and predict the cutting insert behaviour that includes the relation among usage time, wear and power consumption. A basic solution has been provided by Schultheiss et al. [15], where the tool usage is maximized choosing a set of process parameters and engagement geometries that allows the use of all the cutting side of the same insert. This solution allows to reduce the environmental impact of the insert production process but do not include the effect of machining power consumption versus tool wear. Cutting insert wear has been deeply studied by many authors [16,17], especially for what concerns the effect of different process parameters on insert wear. This issue is really important for production companies because it affects the overall cost of the production. Some wear models are actually worldwide accepted, such the Taylor relation that links the cutting velocity (V_c) with the tool life (T).

$$V_c \ T^n = V_1 \tag{1}$$

Where V_1 is a constant experimentally evaluated using cutting tests. The general rule adopted by production companies in this case is to find the optimal compromise between the tool life and the productivity, since an increase of cutting speed decrease the tool life but increase productivity. It is mandatory to consider also that, when the cutting insert get worn, the energy consumption of the process increases due to the dull cutting edge that decrease the front rake angle near the cutting edge itself. And this has a detrimental effect on the required cutting force. So, as the insert wears the required energy increases exponentially and this could lead to a waste of energy that could be reduced but an earlier substitution of the insert itself. An experimental model to describe the relation among tool wear and energy consumption has been developed and later used to assess the optimal cutting insert substitution strategy to minimize the overall environmental footprint of the process, that includes both the contribution of the cutting insert production and process energy consumption.

2. Assessing and optimizing the environmental impact of a turning process

In this paper are considered the effects of cutting parameters, the choice of the lubrication system and the cutting insert substitution on the environmental footprint of a turning process. These could be used to create a holistic model of the process, useful to optimize the setup of the process in order to obtain a greener turning operation. In the following paragraphs, the analyses of each of the three contributions are presented. The developed model is quite general and the optimal setup found in the paper is strongly dependent from the use case, that include machine, material and tooling. However, the methodology adopted in this paper could be reused in a large variety of conditions in order to find the optimal configuration for a specific use case.

2.1. Optimization of cutting parameters

In order to choose the optimal cutting parameters to reduce the environmental footprint of a process it is necessary to create a model of the energy consumption of a machine in different configurations. For this paper, experimental tests have been carried out with AISI S275YC carbon steel and AISI 304 stainless steel. The tool and the insert used are from TaeguTec. The insert code is CNMG 432 MP TT 3500 while the tool is a PCLNR 2525 M12. The test plan has taken into account two parameters: feed rate and the depth of cut. The cutting speed has been considered constant in order not to affect the insert wear at this stage. The tested levels for the parameters are:

- Feed rate: from 0.04 to 0.16 mm/rev (tested: 0.04, 0.06, 0.08, 0.010, 0.12, 0.14, 0.16 mm/rev)
- Depth of cut: from 1 to 2 mm (tested: 1, 1.5, 2 mm)
- Cutting speed: 250 m/min for AISI S275YC and 100 for AISI 304

This plan is constituted by 21 different test configurations. The tool was mounted on a Kistler 9257A 3 axes piezoelectric cell, installed on a Tortona 600 turning machine, that allowed to measure the modulus and direction of the cutting force. The signals have been acquired and processed using a National Instruments 9215 acquisition device at a sampling rate of 1000 Hz with a simultaneous sampling of the three channels (the piezoelectric cell provides a channel for each orthogonal force component). The machine has been equipped also with a system to acquire the total power consumption, constituted by three current gauges produced by LEM (LEM AT 10 B420L, hall effect sensor with open core and a range 0-10A) whose signals were acquired together with the phase voltage with a second NI-9215 cards, at the frequency of 100 Hz/channel. The choice to use three pairs of voltage/current measurement probes, mounted on the system as shown in Fig.1, has been considered in order to measure the power for each phase. It is so irrelevant the configuration of the machine, that could be wye or delta, as presented by Humprey et al. [18]. The signals were post-processed using a Matlab® routine in order to acquire the instantaneous power during each test. The results obtained have been expressed in terms of specific work needed for the removal of 1 mm^3 of material.

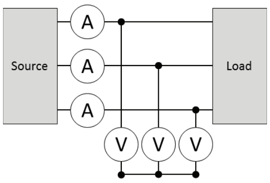

Fig. 1 Architecture of the electrical power measurement system

For the tests have been used a tube in orthogonal cutting condition both for the lubrication and tool life tests. During the tests has been machined about 18 meters of tube for each material, replacing the cutting tool when needed. A picture of the experimental setup is reported in Fig. 2. The tests for the optimal process parameters have been carried out using MQL lubrication. During the tests the quantity of used lubricant has been measured. It has been assumed that the quantity of oil used by MQL has not been able to contaminate the steel scraps that thus do not require any special treatment before the recycling process.

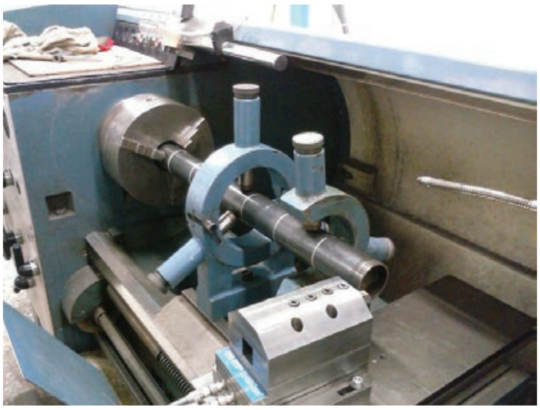

Fig. *2* Experimental setup for cutting tests

The data regarding the energy consumption of the process have been post processed in order to create a model that relates the specific work to the used cutting parameters. The results of the 21 tests have been interpolated with a linear model, whose graphical representation is reported in Fig.3. The R^2 of the regression model is 78%, a value that proves that the model chosen is able to describe effectively the process. There is a huge difference in the specific work needed in the different configuration. The optimal solution is the one characterized by the most demanding parameters in terms of depth of cut (2 mm) and feed (0.16 mm/rev) and it requires 1.54 J/mm^3 while the worst configuration (1 mm depth of cut and a feed of 0.04 mm/rev) requires 2.88 J/mm^3. The energy required in the worst configuration is nearly double respect to the best configuration, enabling a huge saving of the electricity needed to carry out the process using the optimal solution.

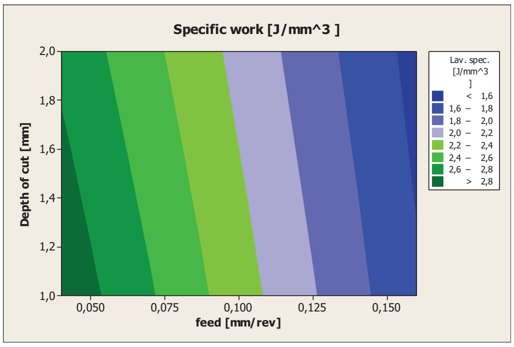

Fig. 3 Power consumption of AISI S275YC (MQL lubrication)

It is important to notice that there are some constraints that limit the increase of the cutting parameters in order to have a more efficient turning process. The first is the strength of the tool: the cutting parameters must be compatible with the tooling and not create the risk of a tool brakeage. The second is the surface finish. In the roughing phase this is not an issue and the most demanding cutting parameters could be adopted, but in the finishing phase the cutting parameters must be selected also considering the required surface finish that usually limits the feed per revolution.

2.2. Analysis of the lubrication

A detailed review of the alternative lubrication processes is reported by Deiab et al. [19] where it emerges how most of the research and industrial efforts are aimed to the reduction, as far as possible, of the use of traditional flooded lubrication and the introduction of an oil free strategy. The main issues of the flooded solution are the safety risk related to the use of lubricant in the working environment, the cost of the lubricant and its environmental footprint. On the other hand, the oil free lubrication strategy, dry machining, increases the tool wear and produces worst surface finish. A convenient solution that reduce the issues related to flooded and dry is the MQL (Minimal Quantity Lubrication). In particular, MQL is actually the industrial state-of-the-art solution for companies that want to implement a more environmental friendly machining processes, since it is able to reduce the problems of dry machining using only a very small quantity of oil. This is especially important when machining hard-to-cut materials. Many authors started from the technical basis of MQL and developed method variants able to improve the process performance, such as Zhang et al. [17] that developed the Minimum Quantity Cooled Lubrication, an approach that combine together two different technologies in order to improve the performance of the traditional MQL increasing its cooling action. Other authors, as Sarikaya and Gullu [20], worked on the multi response optimization of MQL and process parameters when machining hard-to-machine materials, such as the Haynes 25.

Three solutions have been considered and experimentally tested in order to assess the environmental footprint of alternative lubrication strategies: flooded, dry and MQL. The tests have been carried out with the setup reported in Fig. 2. The lubricant used for MQL tests is a Biocut 3000, an oil-alcohol emulsion with a boiling point at 100°C, a density of 1,09 g/cm^3 at 20°C, viscosity of 10 mm^2/s at 40°C and pH of 7,5 and it is fully miscible with water. The MQL system used is produced by Unijet and it is designed for an external lubrication of the tool. For the flooded lubrication a common cutting emulsion has been used.

The first step of the analysis has been the calculation of the energy requirements of each lubrication strategy. This includes both the energy required by the spindle to cut the material and the energy required by the specific support systems. The spindle energy varies due to the different friction coefficients of the cutting process due to the alternative lubrication strategies. While the support systems are air compressor in case of MQL and lubricant pump in case of flooded lubrication.

In order to compare the performances of the alternative solutions, the energy consumption needed to machine a 1 kg of material has been calculated. The tests have been carried out using the best configuration defined with the previous tests, maximum feed rate and depth of cut. The data are reported in Tab. 1.

Table 1 Energy consumption to machine 1 kg of AISI S275YC

Lubrication strategy	Cutting energy (kJ)	Support system energy (kJ)	Total energy (kJ)
Dry	0.43	--	0.43
Flooded	0.39	0.04	0.43
MQL	0.37	0.14	0.51

From the experimentally acquired data it is evident that the lower cutting energy consumption is associated to the MQL strategy (0.37 kJ); this is confirmed also by the trend of the cutting forces acquired using the piezoelectric cell. Flooded lubrication is responsible for a nearly comparable cutting energy (0.39 kJ) and forces, while dry lubrication is characterized by a drastic increase in the cutting energy (0.43 kJ). MQL is more efficient than flooded lubrication in the reduction of the friction due to the higher capacity of the lubricant to arrive in the cutting zone. However, it is necessary to consider also the contribution of the support system of each lubrication strategy. The coolant pump is usually on board on the machine tool while the compressed air needed for MQL is generally produced in a centralized way for the whole production plant. The power consumption of the first has been experimentally acquired connecting the measuring system to the electrical cables of the coolant pump while for the compressed air has been studied the efficiency of some market available machines with the size normally used by a production plant (40-50 kW of maximum power). The machines selected for the evaluation of the compression efficiency of the air are reported in Tab. 2.

Table 2 Compression energy calculation

Compressor Manuf.	Max power (kW)	Air flow@8 bar (dm^3/min) 100% duty cycle @max power	m^3/h @max	Compression energy (Wh/m^3)
Mattei	55	8900	534.0	102.9
Ingersoll Rand	45	6710	402.6	111.7
Compair	45	7800	468.0	96.2
			Mean	**103.6**

This led to the value reported in Tab. 1 where it is evident that the contribution of the support system for MQL is not negligible and decreases drastically the energy performance of this approach. To assess the environmental footprint is necessary to take into account also the impact of the use of lubricant on scrap treatment. In case of dry and MQL the scraps could be considered oil-free, since for MQL the quantity of oil is negligible but in case of flooded the effect of the oil must be quantified. This contribution has been computed thanks to the use of a LCA database (Ga.Bi.) where the treatment of oils soaked and oil free scraps is availble. The result is that scrap processing for flooded lubrication is responsible for 90 grams of equivalent CO$_2$ for processing 1 kg of metallic scraps while dry and MQL strategies are responsible for 9 grams of equivalent CO$_2$ only. In order to compare the electrical consumption and the pollution related to the scrap processing is necessary to use the same metric to evaluate the two contributions. In this case the solution is to convert the electrical consumption in the associated environmental footprint in terms of equivalent CO$_2$. To carry out this step has been considered the production mix in the Italian market, that account for 470 grams of equivalent CO_2 for each kWh of used energy. Summing both the contribution is possible to compare the environmental impact of alternative lubrication solutions; results are reported in Tab.3.

Tab. 3. Environmental impact of scrap treatment

Lubrication strategy	equivalent CO_2 (g) to machine 1 kg of material
Flooded	162 (+100%)
MQL	94 (+16%)
Dry	81

From Tab.3 is possible to underpin how the dry lubrication strategy is able to provide the best environmental performance. It is however important to notice that in this picture it is not considered the negative effect that dry machining has on tool wear, especially for hard-to-cut materials. When working with such materials, the effect of increased tool wear mitigates the environmental advantage of dry lubrication. In conclusion: dry machining is the best option in case of traditional materials but MQL must be considered the best option when hard-to-cut materials are machined. A detailed analysis of cutting inserts environmental impact is reported in the next paragraph.

2.3. Tool replacement strategy impact

The cutting inserts are mostly made of tungsten carbide and are characterized by high cost. Due to its cost, a cutting insert is usually replaced only when quality and dimensional issues arise in the finished product due to excessive tool wear. A value that is usually taken as a reference in the production shop is when the wear of the cutting edge reaches a threshold value of 300 μm. The limit of insert end-of-life substitution strategy is that worn tools are responsible for a higher electrical energy consumption for the machining process due to progressively higher cutting forces. The approach developed proposes a new cutting insert substitution strategy based on the overall environmental footprint of the process that takes into account both the production and use phase of the insert to define its optimal life.

The production phase of the insert is really critical because the material used, tungsten carbide, requires energy intensive processes. Considering only the extraction of tungsten, it is required an huge energy consumption, 12 kWh/kg of raw material [21]. This value is really high, especially if compared to the production of a high alloyed steel that has a production energy of about 2 kWh/kg. The energy consumption could be expressed in term of environmental impact considering the CO_2 equivalent emission including also the sintering process, whose environmental impact is extracted from [15]. After the sum of the two contributions, the resulting environmental impact of the cutting insert is equal to 27.8 kg CO_2 equivalent for each kg of finished inserts. The weight of the cutting inserts used for the experimental tests is 12 grams.

To consider the effect of tool wear on the energy required for the machining process is necessary to carry out some experimental tests. During these tests, the cutting forces and the energy requirements have been measured along time in order to verify the relation between wear and cutting forces/electrical consumption. The cutting inserts wear have been measured using an optical microscope every 20 cm of machined material (tube). The tests have been carried out using the optimal cutting parameters selected to reduce the specific energy, as reported in the first paragraph. All the tests have been carried out using dry lubrication, as suggested by the lubrication systems analysis. Each test has been stopped when the insert wear reached 300 μm, value usually considered the limit of insert acceptability due to the effect on geometrical error of the finished product and the detrimental effect on the quality of the machined surface. For each material, the final objective has been to wear at last 4 cutting inserts. From the analysis of the results it is interesting to notice the increase of the cutting power needed to carry out the operation along the time. This trend is reported in Fig.4.

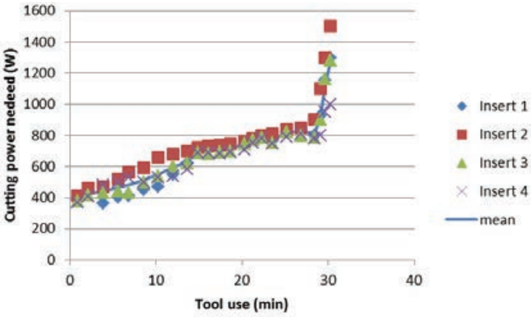

Fig. 4 Cutting power along time for stainless steel

In order to evaluate the optimal substitution rule of a cutting insert, the environmental impact of alternative solutions have been computed considering different insert substitution time. The three contributions that have been computed to calculate the total environmental impact are:

- Cutting power: is the calculated mean power needed for machining 1 mm^3 of material for different tool wear stage. Basically, it is the integral of the curve reported in Fig.4 at different tool life divided by the removed material till this time.
- Constant power: is due to the support systems of the machine, like the NC. This is a constant value and does not affect the optimization process.
- Tool impact: is the environmental impact associated to the tool for different tool substitution timings. It could be calculated dividing the environmental impact of the inserts by the material volume machined till its substitution.

These three contribution are graphically represented in Fig.5 while a detail of the last minutes of usage of the tool is reported in Fig.6. From these pictures it is possible to notice that the total environmental impact decrease with the tool usage. Only near the end of life of the tool, 28 minutes, when the cutting force have an exponentially increasing trend due to excessive tool wear, the total specific environmental impact starts to increase. This means that the insert substitutions strategy generally adopted based on economic and quality issues is consistent with the minimum achievable environmental impact. This is due to the really high environmental impact associated to the production of a cutting insert that push for a solution that maximize the usage of the insert, also if the power needed for the machining increase with the tool wear.

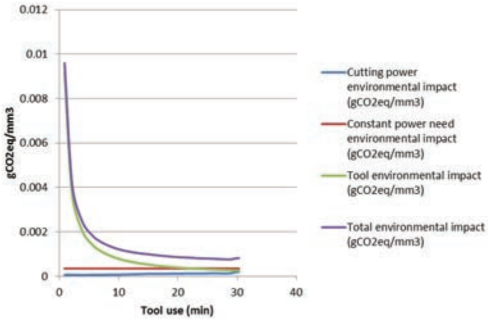

Fig. *5* Specific environmental impact

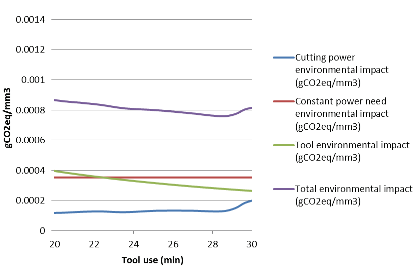

Fig. *6* Specific environmental impact (zoom)

3. Conclusions

This paper has the aim to present an analysis of different contributions that could affect the environmental impact of a turning process. In particular, the paper presents an analysis of the best process parameters, lubrication system and cutting inserts substitution strategy.

Regarding the process parameters, from the experimental tests emerges how the best setup is the one that maximize the material removal rate, so higher depth of cut and feed, compatibly with the strength of the tool and the required surface finish.

In case of lubrication strategy, the analysis shows how the dry lubrication is characterized by the lowest environmental impact. MQL has a lightly worst performance (+16% of environmental impact) while flooded accounts for an impact that is double respect to dry machining. As a conclusion, dry must be used as a solution whenever possible. In case of hard-to-cut materials that would suffer a too high tool wear when using dry machining, MQL is the best alternative.

At the end, an alternative substitution rule for cutting inserts has been proposed, based on the overall environmental impact of the process. For this specific tooling, it emerges how the best solution is to change the inserts as late as possible, 28 minutes for the test case, consistently with the strategy already adopted in most of the machine shops in order to reduce the operational cost of their processes.

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