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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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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