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Energy efficient machining with optimized coolant lubrication flow rates

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Abstract

Nowadays, reducing the energy consumption is an important step to optimize machine tools. In general use, high pressure pumps of inner cooling lubricant supply are dominant energy consumers in machine tools and thus offer great possible savings. This paper presents and discusses several approaches to optimize the energy consumption of machine tools by controlling and reducing the coolant flow rate. Measurements of the machine power input show total saving potentials of up to 37 percent, while investigations of tool wear examine the aspect of technological risks. The feed rate is identified as a significant influencing factor, which interacts between the tool wear and the optimal lubrication flow rate in milling and drilling operations.

1. Introduction

Energy costs have come into focus of metalworking industry in the last decade since they have increased continuously and account up to 20 percent of total cost of ownership for machine tools nowadays [1]. However, energy efficiency measures should not be at the expense of accuracy, dynamic and reliability, which are still the dominant indicators for the productivity of machine tools. Apart from directly economic aspects ecologically motivated incentives are also becoming increasingly significant since the industry sector has a 42.6 percent share of world electricity consumption [2]. Due to climate change and its aftermath on our society, politics have become aware of industry’s impact on primary energy consumption and thus carbon emissions in the past few years. As a consequence, several political restrictions have come up that force manufacturers and users of machine tools to reduce their energy consumption [3,4].

High pressure cutting fluid pumps were identified as main consumers in a large number of investigations [5,7]. However, Klocke et al. show that the power-demanding high-pressure technology can yield overall energy savings. For the investigated turning process, a significant increase of the achievable cutting speed shortens the primary processing time by 50 percent and therewith the energy amount per workpiece by 40 percent without influence on tool wear [8]. Sangermann shows possibilities to reduce the hydraulic power at a constant level without increasing tool wear [9]. Nevertheless, Rief et al. present drilling operations for example, where conventional flood cooling has advantages in tool life and energy efficiency over high pressure technology [10]. In general, a transferability of existing results is hardly possible because of a wide range of influencing parameters [11]. Further investigations are required to get a profound knowledge of the effects on the machining process [8,9,11]. From the environmental point of view, it must be the goal to achieve maximum productivity with minimum energy input that mainly depends on pressure and flow rate [8]. The latter is applied to be the crucial parameter for all main tasks of cutting fluid (cooling, lubrication, chip transport and in some cases chip control) [11]. It can be ensured by implementing a flow rate control as shown in [6]. In comparison to a
conventional pressure control with a regulating valve, it offers considerable energy savings in machining centers. The power demand of the cutting fluid unit which is equipped with a 40 bar pump for the inner coolant supply, was reduced by 32 percent in a demonstration process. Thereby, especially in drilling operations, the pressure and thus the energy consumption are automatically lowered because of the reduced flow resistance in idle times.

The approach of the work presented in this paper is an extension of the flow rate control shown in [6,12]. An additional lowering of pump power can be realized by a need-based selection of flow rate setpoints. These values must be chosen accurately with regard to actual process parameters to avoid losses of productivity or increased tool wear. Therefore, the effect between flow rate and tool wear was investigated for different process types. By means of a need-based flow rate supply the energy saving potential was determined experimentally on a modified machining center. The studies were conducted in collaboration with the companies DMG MORI SEIKI, Sandvik Coromant, Grundfos and Bosch Rexroth Interlit.

2. Experimental setup

Two representative machine tools are chosen for the investigations. Milling and drilling operations are considered as well as cylindrical turning and grooving. The material for all experiments is duplex steel (1.4462).

The first testing machine is a machining center DMG DMU 65 monoBLOCK® for milling and drilling operations (Fig. 1), that is equipped with a cutting fluid unit made by Bosch Rexroth Interlit. Its screw pump for high pressure supply is frequency converted and hence represents the best available technology concerning energy efficiency. It achieves a maximum pressure of 80 bar and a maximum flow rate of 31.9 l/min. An additional implementation of flow rate sensors enables a flow rate control of the inner cutting fluid. By means of the G-code, the operating mode can be switched from pressure control to flow rate control. Additional NC commands specify the setpoint values that are transferred by a PROFIBUS connection to the frequency converter of the pump. Fig. 1 shows the energy distribution of this machining center for a demonstrator machining process with a constant pressure of 80 bar. In this case, the frequency converted high pressure pump requires 46 percent of the total energy input and thus offers most potential savings. The cutting tools for drilling and milling are of type SANDVIK CoroMill® and CoroDrill®.

The second machine tool is a GILDEMEISTER CTX 520 L® lathe for the regarded cylindrical turning and grooving applications and contains a centrifugal pump made by Grundfos. It is frequency converted and pressure controlled and achieves a maximum pressure of 20 bar and a flow rate of 50 l/min. The turning tools used are of type SANDVIK T-Max® P and CoroCut® Q and contain jets for directed coolant fluid supply.

3. Tool wear

The influence of the variation of the volume flow rate of the coolant on the tool life time is investigated for external cylindrical turning and grooving on the lathe and for side milling and drilling on the machining center.

The influence of volume flow rate of the coolant on the tool life time is analyzed for external cylindrical turning. Therefore the tool wear is investigated by measuring the width of flank wear land (VB) with respect to the cutting length of the tool (Fig. 2). VB = 300 μm is assumed to be the terminal width of flank wear land which indicates the maximum cutting length for a given tool.

The cutting tests are performed for five equally distributed volume flow rates in the range of 2.2 to 6.8 l/min, the machining parameters are given in Fig. 2. In Fig. 3 the trend of VB with increasing cutting lengths lc are shown for variable volume flow rates. It can be seen that the maximum cutting length is comparable for flow rates in the range of 4.5 to 6.8 l/min but decreases rapidly for smaller flow rates. Consequently, the flow rate for this machining process can be reduced to 4.5 l/min without affecting the tool life time. This is addressed as minimum required flow rate.

Subsequently, it was analyzed how the process parameters affect the minimum required flow rate by increasing the cutting speed and the feed rate separately, which is shown in Fig. 4. It compares the maximum cutting length for variable volume flow rates and process parameters. It becomes evident that the tool life time – indicated by the maximum cutting length – is decreased with increasing feed rate and cutting speed but the minimum required flow rate is independent of the process parameters.

3.2. Wear investigation on a machining center

After demonstrating the existence of a minimum required volume flow rate of the coolant for turning processes this finding is to be confirmed for more complex machining
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processes like milling and drilling. Consequently, a standard process for milling and drilling is defined and tool life is monitored for variable volume flow rates of the coolant. Subsequently, the process parameters \( f \) and \( v_c \) are varied to study their influence on the optimum volume flow rate.

The lifetime of the tools is investigated by measuring the tool wear for three predefined cutting volumes for milling and number of holes for drilling, respectively. The maximum cutting volume of \( V = 260 \text{ cm}^3 \) is used as an abort criteria, which gives a tool life time of 20 min for the standard parameters. For milling tools the wear is detected at the corner and the major cutting edge and additionally the increase of feed normal force and the chip form are evaluated.

The wear of the drilling tool is quantified at the cutting edge, at the margin and at the chisel edge. From these data, for each process a wear coefficient is calculated ranging from 0 (= no evidence of wear during the whole process) to 6 (= instantaneous failure of the tool) which is taken as a measure for the overall performance of the tool. The advantage of this approach is that the process is rated by just one number which accounts for different wear forms and their progressions. At the same time the measurement effort is minimized. In general, wear coefficient less than 2 denotes a process which is capable regarding the aspired tool life. A more detailed explanation of the derivation of the wear coefficient is given in appendix A.

Both for milling and drilling the influence of feed on the minimum required volume flow rate is detected (Fig. 5). Considering the standard milling process (Fig. 5A) best results regarding tool life are achieved with dry machining. With increasing feed rate at first dry machining and later even machining with low volume flow rate becomes unfavorable. The main failure mechanisms are strong break outs at the cutting edge. A similar effect is observed for the drilling tool (Fig. 5B). While all processes show wear coefficients less than 2, still with rising feed rates the wear coefficients increase with decreasing volume flow rates. The trend for milling and drilling is the same, what results in higher minimum required volume flow rates for increasing feed rates.

Variation of the cutting speed shows a different behavior. Milling with increased cutting speed of \( v_c = 80 \text{ m/min} \) coolant becomes unfavourable, independent of the applied volume flow rate (Fig. 5C). The tools fail due to macroscopic break outs at the cutting edge and the corner of the tool. For drilling an increase of the cutting speed shows no distinct effects, but when the cutting speed is lowered to \( v_c = 30 \text{ m/min} \) high volume flow rates of the coolant are mandatory. After the first 15 holes no explicic signs of tools wear are observed but then the drilling tool tends to break spontaneously. Considering milling the high temperatures at the cutting edge that go along with the increased cutting speed may cause a thermo-shock when the tool is exposed to coolant. This may explain the
increase of tool chipping of the cutting edge. For drilling with reduced cutting speeds higher volume flow rates of the coolant are required to enable a safe chip transport and avoid spontaneous breakage of the drilling tool.

4. Energy saving strategies

The tests presented above reveal that the flow rate can be reduced within a certain range without changing tool life. For the example of external cylindrical turning the optimal flow rate is 4.5 l/min. In consequence, the pump power decreases by 67 percent, as shown in Fig. 6. This indicates a considerable energy saving potential for this single process step. Investigations on the impact on a complete machining program consisting of several different cutting conditions and idle times were conducted at the testing machining center DMU 65.

4.1. System characteristics

For a better understanding of the supply unit, Fig. 7 illustrates the measured system characteristics of the screw pump using different tools. According to the applied tool, the pressure is a function of the flow rate. This connection defines the operating point for the screw pump and its power input. The achievable savings by reducing the flow rate can be demonstrated by means of an example for the 10 mm milling tool. Assuming that the flow rate can be reduced by 28 percent without inadmissible impact on tool wear and manufacturing quality, the pressure decreases to one half. Meanwhile, the pump power which primarily depends on the pressure gets reduced by up to 77 percent. As a result it can be noted that even a small lowering of the flow rate values has a comparatively strong influence on the energy efficiency.

4.2. Approaches for need-based flow rate reduction

The current process parameters are utilized to set the values of the flow rates for the inner cutting fluid. Three possibilities are considered, from which they can originate: a manual setting, a CAx and a simulation based setting. According to these sources, different levels of detail can be achieved. Firstly, the flow rate values instead of pressure values can directly be entered by the machine user into the human machine interface. The basic information may be their
experience or default values corresponding to the system characteristics shown in Fig. 7. Because of the limited process insight it is obvious that this manual setpoint selection can only be reasonably realized with one value entry per tool change. In this first approach, they are chosen as high as possible referred to the corresponding characteristic curve.

Fig. 7. Pump characteristic curves of DMU 65 with testing tools.

Secondly, CAx software can be used as origin of selection. It obtains multiple stored process information, which gets lost after G-code creation. The automatic generation of setpoint value including commands is accomplished at each tool change and each distinction between roughing and finishing. The hypothetical assumption is made that finishing operations require less cutting fluid flow rate than roughing operations, according to the example shown in Fig. 7.

The third approach is based on enhanced process knowledge that is generated by a cutting simulation (CutS) presented in [13]. This simulation tool calculates the material removal rate and achieves a higher level of detail compared to the other approaches. It is therefore possible to add an individual setpoint command to each NC block. The underlying hypothetical assumption is that these values can be set in proportion to the particular removal rate. Here the flow rate reached at full pressure corresponds to the maximal removal rate that is specified by the tool manufacturer and indicated in its catalog. The lowest flow rate that can be realized without completely turning off the pump (lower end of characteristic curves in Fig. 7) corresponds to a removal rate of zero.

The three approaches described above as well as the reference scenario with a constant pressure shown in Fig. 1 were executed at the modified machining center. Fig. 8 illustrates the resulting flow rates.

In general, the graphs depict an increasing reduction of delivered cutting fluid and a rising level of detail over the three approaches. The differences between the maximum flow rates of reference and approach 1 are founded in the restriction that only whole-number values can be transmitted.

4.3. Effort and energy savings

Table 1 lists the technical requirements and the resulting energy measurements for the test machining operations described above. The existence of a flow rate sensor incurs additional costs, but makes the principle of controlling the flow rate possible. The approaches 2 and 3 require software functions that are not usually available, but can be implemented into CAx software basically.

While the pump energy can be reduced by up to about 80 percent using the third approach, in this measurement the energy input of the whole machine tool is lowered by up to 45 percent. But the latter includes not only the pump energy savings but also a reduction of other autarkical working machine components, such as the cooling aggregate or the lifting pump, which is relieved by the lowering of inner coolant supply in turn. These ancillary effects are due to long-term working periods being larger than the machining time of about 12 minutes. In consequence, an exact comparability of the machine energy measurements does not exist. But when assuming that the rest of the machine requires the same amount of energy as in the reference scenario, the maximum energy saving of strategy 3 amounts 1.46 kWh. So it can be said that the maximal overall energy saving potential is at least 37%.
For turning the optimum volume flow rate did not depend on the maximum volume flow rate. Thus the optimum volume flow rate is not equal to the maximum volume flow rate.

For turning the optimum volume flow rate did not depend on the process parameters tested in this study. Considering side milling and drilling the optimum flow rate strongly depends on the process parameters. Increasing feed rates require higher volume flow rates while increasing cutting speeds lead to the opposite effect.

Energetic analyses of the machining center DMU 65 reveals that the high pressure cutting fluid pump is the main consumer and quantify the possible savings of three reduction strategies. They are based on a flow rate control with adjusted setpoint values and differ in their complexity. Considering all approaches presented, it can be noted in general that a high implementation effort is worthwhile. The higher the complexity of a reduction strategy is accepted, the more energy can be saved, in this scenario up to at least 37 percent.

In future, the relations between flow rate and tool wear need to be investigated with regard to further materials, tools and cutting conditions. Because of the wide range of strongly influencing parameters, only specific conclusions are expected. However, it might be possible to combine them with detailed process foreknowledge gained by cutting simulation to forecast the optimal fluid flow rate. Therefore, its implementation into CAx software or the machine control is aspired.

5. Conclusion

It has been shown that the maximum volume flow rate of the coolant does not necessarily lead to the best tool performance regarding its wear behaviour. For external cylindrical turning the tool life remains constant by lowering the volume flow rate from 6.8 to 4.5 l/min allowing for energy savings of up to 67%. Thus the optimum volume flow rate is not equal to the maximum volume flow rate.

Appendix A. Calculation of the wear coefficient

For milling test the tool wear is measured both directly by looking at the corner wear and the wear at the major cutting edge of the tool and indirectly by the increase of feed normal force and the shape of the chips. In order to get an overall description of the tool wear each of the four cutting edges of the milling tool as well as the chip shape and the force gain is assigned a value ranging from 0 to 6. In Fig. 9 the classification of the cutting edges is given exemplarily. The classification of chip shape is done in a similar way. Since for a given cutting process the tool wear is measured for three cutting volumes, each process is described by 18 wear values. These values are combined to one number which will be referred to as wear coefficient ($C_w$), describing the overall performance of the tool.

$$C_w = \sqrt{\frac{\sum_{ij} w_{ij}^3 + \sum_i \Delta f_i^2 + \sum_i c_i^2}{18}}$$

where $w_{ij}$, $\Delta f_i$ and $c_i$ describe the classification of cutting edge, force gain and chip shape respectively. By applying the 3-norm outlying high values in one class get a heavier load on the wear coefficient.

The evaluation of tool wear for the drilling tests follows a similar approach. In this case tool wear is measured only directly but the wear at the cutting edge, at the margin and at the chisel edge are classified separately. Again, the classification ranges from 0 to 6. Analog to the calculation...
above a wear coefficient is calculated with these values using the 3-norm.

Fig. 9. Classification of the wear at the cutting edges of the milling tool.