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The Impact of Fluid Supply on Energy Efficiency and Process Performance in Grinding

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An approach is presented to evaluate the energy efficiency of grinding processes by the total specific energy in relation to the process limits, e.g. starting thermal damage at a certain specific removal rate. The paper deals with grinding experiments on hardened steel workpieces covering a broad range of different types of fluid supply nozzles, fluid flowrates, and removal rates with and without high pressure tool cleaning. In the investigations, process configurations were identified leading to high energy efficiency in combination with highest achievable removal rates. Furthermore, the results confirm that the process limit is significantly influenced by specifically adapted fluid supply conditions e.g. flowrate and jet speed.

Grinding, Energy efficiency, Fluid supply configuration

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1. Introduction and state-of-the-art

In grinding, most of the heat generated due to high friction between the abrasive grains and the workpiece material is dissipated through the surface layer of the workpiece [1] and causes major challenges for the generation [2] and assessment of favourable surface integrity [3]. If the thermal load of the workpiece exceeds certain limits, thermal damage of the workpiece material (e.g. grinding burn) occurs which is accompanied by changes in hardness, a change in microstructure or a change in the residual stress state [4]. Morgan et al. [5] show that a critical specific material removal rate exists as a function of the useful flowrate of the metal working fluid (MWF) in the contact zone for constant process parameters in order to prevent thermal damage to the workpiece (tempering effects, white layer formation). Thus, thermal damage to the component (grinding burn) can be used to evaluate and describe the efficiency of fluid supply parameters and essential performance limits of grinding processes [6, 7]. The efficient supply of MWF to the grinding contact zone depends on various parameters such as the jet velocity, the jet shape caused by the fluid supply nozzle, and the nozzle position [5]. In this context, Heinzel et al. [8] have examined the influence of different fluid supply conditions on the temperature development in the contact zone during grinding. A further aspect in connection with the energy efficiency consideration of grinding processes is represented by tool cleaning to reduce or avoid clogging. Clogging results in increasing process temperatures and process forces due to increased friction, which is why the workpiece is subjected to greater mechanical and above all thermal load [9].

For this reason, many research activities focused on increasing the energy and ressource efficiency of machining processes by using process specific minimum MWF flowrates, since this makes up a large part of the energy consumption of machine tools [10, 11]. Together, hydraulics and the fluid supply are responsible for about three quarters of energy consumption of a grinding process [12] and account for a large proportion of total machine tool operating costs. Solutions for reducing energy consumption and increasing energy efficiency, especially during the manufacturing process, are therefore essential requirements in science and industrial practice [12]. In addition to an approach related to the machining process, the literature also contains concepts that take a holistic view of machine tools, including the machine states "process", "idle" and "standby". Schudeleit et al. have developed a method which allows the calculation of a "Total Energy Efficiency Index (TEEI)" under consideration of the mentioned machine operating conditions [13]. As a result, it was stated that mainly the fluid supply and the spindle power influence the energy efficiency of manufacturing processes. However, the data required for this are not always fully available or cannot be recorded continuously on the machine tool.

For the evaluation of manufacturing processes with regard to energy efficiency, the specific energy is a suitable quantity, since it can be used to describe the ratio of energy input to a suitable functional unit of the product [14, 15]. This empirical approach has already been validated for the evaluation of the relationship between process parameters and energy efficiency for processes with geometrically defined cutting edges [16, 17] and was later transferred to grinding [14, 18]. In grinding processes, the specific grinding energy (ratio of spindle power to material removal rate) provides the energy consumption at the grinding spindle during the machining of a material volume unit and is therefore one suitable measure for evaluating the energy efficiency during grinding [18, 19].

It can be stated that different variables can be used to assess the energy efficiency of manufacturing processes. However, not only the spindle power is decisive for the assessment of energy efficiency, but also fluid supply systems must be included in the analysis. In addition, the quality of the workpiece, in particular the surface integrity which is often limiting the process performance, has to be taken into account in order to allow for a comprehensive view on the energy efficiency of manufacturing processes or the entire machine tool. This paper presents an approach which is making use of the specific energy to describe the energy efficiency in grinding considering varied fluid supply conditions as well as the surface properties of ground workpieces in terms of grinding burn. Also, possibilities and limits in view of increasing the energy efficiency in grinding can be observed based on this empirical method.

2. Research approach

Aim of the research approach presented within this paper is to study the impact of the fluid supply on the process limits and energy efficiency of grinding processes. In this regard, frequency controlled pumps for the fluid supply are used so that the energy consumption needed for the fluid supply is optimised already and is dependent on the fluid flowrate. Two different conditions can lead to an increase of the energy efficiency in grinding: On the one hand side, the energy efficiency can be enhanced by a reduction of the flowrate for the fluid supply at constant material removal rate if the workpiece is not affected by thermal damage. On the other hand side as the principle sketch in Figure 1 shows, a higher fluid flowrate (probably in combination with tool cleaning) can lead to an increase in the material removal rate by maintaining the desired state of the ground workpiece (no grinding burn) and less forces and power due to better lubrication. This leads also to an increase in energy efficiency of the process.

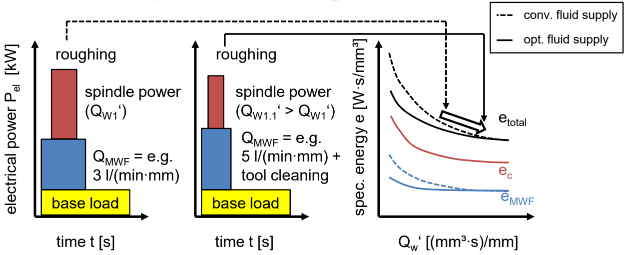

Figure 1. Research approach for increasing energy efficiency in grinding

In order to assess the state of the workpiece material, Barkhausen noise analysis is used to examine if the ground workpieces are affected by thermal loads. Therefore, the ground workpieces were analysed regarding the Barkhausen noise value RMS at five positions along the workpiece length of 250 mm. The result of the Barkhausen noise measurement is then used to observe the process limit for the energy efficiency assessment. To describe the energy efficiency of the performed grinding tests, the specific energy e_{total} is used and calculated by:

$$e_{total} = e_{bl} + e_c + e_{MWF} = \frac{P_{bl}}{Q_w} + \frac{P_c}{Q_w} + \frac{P_{MWF}}{Q_w} \left[\frac{W \cdot s}{mm^3}\right] \quad (1)$$

where e_{bl} denotes the specific energy of the base load of the machine tool (here with a constant value of P_{bl} of 4000 W), e_c the specific energy of the spindle, e_{MWF} the specific energy of the fluid supply and Q_w the material removal rate. The power values P_{bl}, P_c, and P_{MWF} are measured by using a power analyzer WT500 from Yokogawa.

Two different nozzle designs are selected: On the one hand side, a tangential flat nozzle design is used which is commonly applied for fluid supply in industrial practice for face grinding. On the other hand side, a so-called modular nozzle is used which consists of a certain number of small jet nozzles (cf. Figure 2). Due to this design, a fluid jet with a high coherent length is resulting which is contributing to an increased cooling and lubricating effect.

For the grinding tests, a flowrate of the MWF Q_{MWF} of 100, 175 and 250 l/min is used to investigate the influence of varying fluid supply conditions on energy efficiency. The flowrates are selected in order to emulate fluid supply conditions (also in view of jet speeds) in line with current industrial practice and its further improvement. In addition, the effect of tool cleaning on the energy efficiency is investigated by using a flat nozzle with a constant flow of the MWF $Q_{MWF,cleaning}$ of 20 l/min at $p_{MWF,cleaning}$ of 20 bar. The impact angle (perpendicular to the grinding wheel surface) and the distance between the cleaning nozzle and the grinding wheel surface are chosen according to the optimal values identified in [9]. The effect of the cleaning nozzle is evaluated by optical measurement of the wheel clogging (cf. [9]). If the cleaning nozzle is used, a constant value for the cleaning nozzle power $P_{MWF,cleaning}$ of 3300 W is additionally taken into account for e_{MWF} (together with the energy consumption for fluid supply). The nozzle designs are assessed with regard to power consumption for MWF supply and MWF jet speed (cf. Table 1). The jet speeds are calculated from the fluid flowrate and the nozzle's outlet cross-sections.

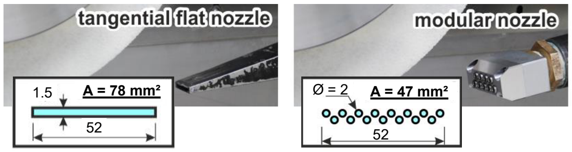

Figure 2. Investigated fluid supply nozzle designs

Table 1 Power consumption (P_{MWF}) and jet speed (v_{jet}) depending on nozzle's design and fluid flowrate (Q_{MWF})

	Q_{MWF} = 100 l/min	Q_{MWF} = 175 l/min	Q_{MWF} = 250 l/min
Tangential flat nozzle	P_{MWF} = 1.02 kW v_{jet} = 22 m/s	P_{MWF} = 3.25 kW v_{jet} = 37 m/s	P_{MWF} = 8.74 kW v_{jet} = 53 m/s
Modular nozzle	P_{MWF} = 1.91 kW v_{jet} = 35 m/s	P_{MWF} = 8.13 kW v_{jet} = 62 m/s	P_{MWF} = 19.61 kW v_{jet} = 88 m/s

For the grinding tests, workpieces with a width of 60 mm, a length of 250 mm and a height of 20 mm made of the material AISI 4240 (42CrMo4) in a hardened and tempered condition are used (workpiece hardness 46±2 HRC). Rough grinding tests with depth of cut a_e = 0.3 mm and width of cut of $a_p = b_s$ = 50 mm at constant grinding wheel speed v_s = 35 m/s are performed. The grinding experiments are carried out on a face grinding machine tool Micro-Cut A8 from company ELB-SCHLIFF. To increase the thermal load during grinding, the specific material removal rate Q_w' is varied by the tangential feed speed v_{ft}. The grinding wheel (specification: 9A60H16VC2, vitrified bonded corundum grinding wheel) with a diameter of d_s = 400 mm is dressed prior to each test by using a profile roller with a dressing speed ratio of q_d = 0.8. As grinding fluid, a water-based emulsion Rhenus R-Flex with a concentration of 4% is used.

3. Experimental results

A change in the thermal load during grinding due to the variation of the fluid supply conditions not only affects the power consumption of the entire grinding process, but also the effective process forces. In this context, the development of the process forces as a function of the fluid supply nozzle and the MWF flowrate without the use of wheel cleaning is considered at first. Figure 3 shows the development of the tangential force and the spindle power under the variation of the MWF flowrate (Q_{MWF} = 100, 175, 250 l/min) by using the tangential flat nozzle without tool cleaning. The data presented here show the mean value from a total of six points of the force measurement data (measurement of process start, middle and end; each grinding test was repeated one time). The measured spindle power P_c is used to calculate the specific energy e_c. The tangential force is plotted additionally as these values are more sensitive to variation of process parameters. For all performed grinding processes it can be stated that almost constant grinding forces across the grinding lengths have been examined. As maximum deviations, +/-3% for the specific forces was observed. Due to the low deviation, error baes are not shown in the figures. Figure 3 also shows the process limit "PL" for the three different MWF flowrates defined by initial occurence of grinding burn (Barkhausen noise analysis). By increasing the MWF flowrate from 100 l/min to 250 l/min, the process limit shifts from Q_w' = 7.5 mm³/(mm·s) to

$Q_w{}' = 14\ \text{mm}^3/(\text{mm·s})$. It can be assumed that the thermal load acting on the workpiece during the grinding process can be reduced by improved cooling and lubricating effect of the contact zone with increasing MWF flowrate. Figure 3 also shows that the tangential forces decrease with increasing amount of fluid. It should be noted here that the high flowrates of MWF and the associated high pressures at the nozzle already result in a good cleaning effect of the grinding wheel, which also contributes to a process limit at higher removal rate. This becomes particularly clear when using the modular nozzle, where the process limit is increased from $Q_w{}' = 10\ \text{mm}^3/(\text{mm·s})$ to $Q_w{}' = 19\ \text{mm}^3/(\text{mm·s})$ by increasing the MWF flowrate from 100 l/min to 250 l/min (cf. Figure 4).

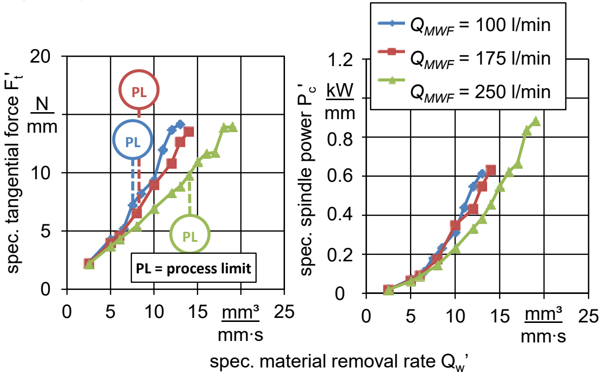

Figure 3. Tangential force and spindle power for grinding tests with tangential flat nozzle (without tool cleaning)

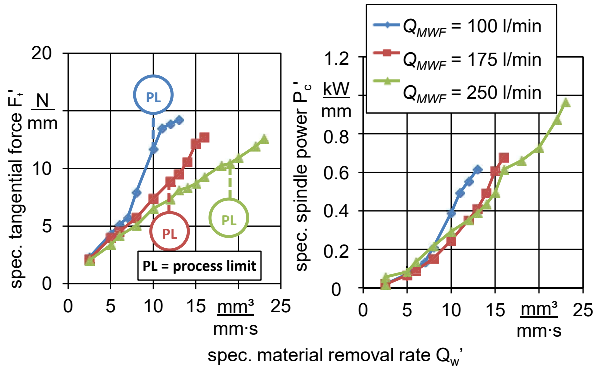

Figure 4. Tangential force and spindle power for grinding tests with modular nozzle (without tool cleaning)

For the tangential flat nozzle in combination with tool cleaning, no increase in the process limit compared with the process strategy without tool cleaning can be determined, although the clogging of the grinding wheel is significantly reduced. This might be due to the fact that the restricted jet coherency of the tangential nozzle limits the cooling and lubrication effect in the contact zone which might not be compensated by additional tool cleaning.

Figure 5 shows the development of the process forces and the spindle power for the use of the modular nozzle with tool cleaning showing similar interrelations, whereby the increase of the MWF flowrate causes a slight reduction of the tangential forces. Nevertheless, the process limit can be slightly increased from $Q_w{}' = 19\ \text{mm}^3/(\text{mm·s})$ to $Q_w{}' = 20\ \text{mm}^3/(\text{mm·s})$ ($Q_{MWF} = 250$ l/min) compared to the grinding processes without the additional tool cleaning. The results on the degree of clogging show that even without the use of the cleaning nozzles, clogging of the grinding wheel surface is low (cf. Figure 6). Thus, the effect of the further reduction of clogging by the additional tool cleaning on the process limits can be identified, but is small.

Figure 7 examplarily shows the results of Barkhausen noise analysis with regard to thermal damage for the grinding tests with tool cleaning (average value of five measurements with minimum/maximum deviation). The base value and the scatter band for thermally undamaged workpieces (area marked off by horizontal lines within figure 7) are observed by analysing the workpieces after the heat-treatment prior to grinding. It can be stated that the thermally damaged samples can be clearly distinguished from the non-thermally damaged samples. The thus observed process limits are used for the energy efficiency analysis on the basis of the specific energy e_{total}.

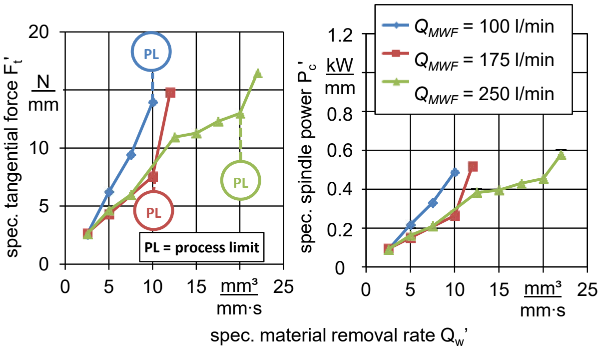

Figure 5. Tangential force and spindle power for grinding tests with modular nozzle (with tool cleaning)

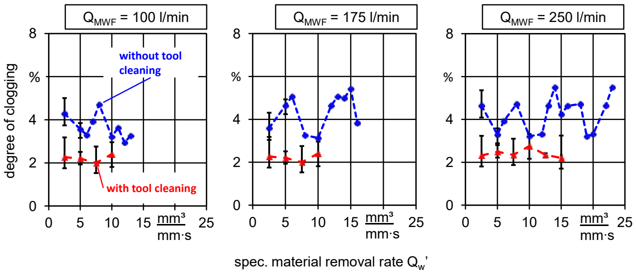

Figure 6. Degree of clogging of the grinding wheel for grinding tests with modular nozzle (with and without tool cleaning)

For the individual nozzle designs, the values for the specific energies e_{total} - calculated according to equation 1 - are plotted as a function of the specific material removal rate in relation to the process limits (cf. Figure 8 - without the use of tool cleaning). Based on the results, it becomes clear that, with regard to energy consumption, strong advantages can be seen when the tangential flat nozzle is used for fluid supply as the lowest values of the specific energy are determined here. However, there is also a high potential for increasing energy efficiency with the modular nozzle, since here an increase in the process limit of approx. 25% compared to the tangential flat nozzle is possible.

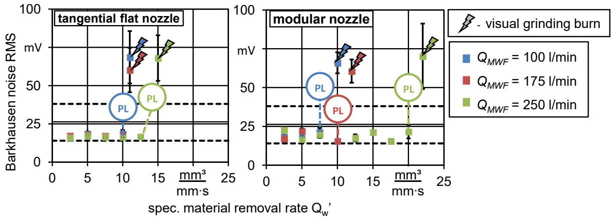

Figure 7. Barkhausen noise analysis for grinding tests with modular nozzle and tangential flat nozzle (with tool cleaning)

As it can be derived from Figure 9, higher values for the specific energy e_{total} result from the additional energy consumption by the tool cleaning. Although the results for the tangential flat nozzle shows a lower energy consumption compared to the modular nozzle, the process limit for the modular nozzle is significantly higher with respect to the related specific material removal rate (tangential flat nozzle $Q_{w,max.}'$ = 12.5 $mm^3/(mm \cdot s)$; modular nozzle $Q_{w,max.}'$ = 20 $mm^3/(mm \cdot s)$). However, the process limits for both nozzle designs can only be slightly increased by using tool cleaning compared with the process strategy without tool cleaning.

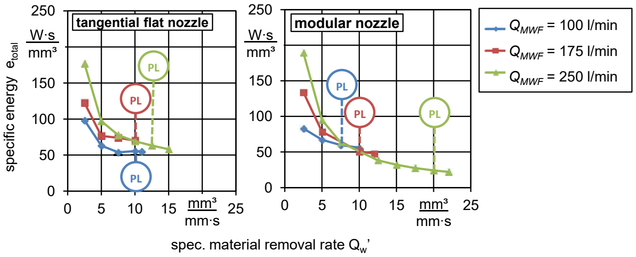

Figure 8. Specific energy e_{total} for grinding tests without tool cleaning

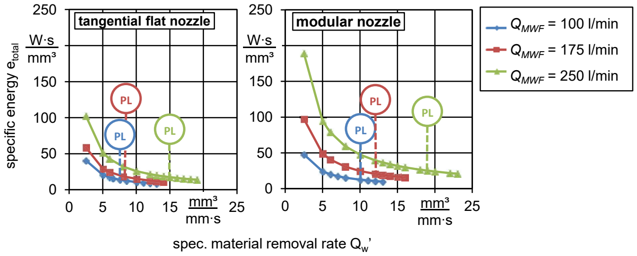

Figure 9. Specific energy e_{total} for grinding tests with tool cleaning

Based on the used approach for assessing the energy efficiency by the specific energy, possibilities for increasing energy efficiency of grinding processes can be derived depending on the nozzle design and the fluid supply conditions. It should be emphasised in this context that the use of tool cleaning compared to the process strategy without tool cleaning contributes to further positive aspects such as reduced wheel wear as well as more repeatable and more constant work results, which are not shown here in detail.

4. Conclusion and outlook

The presented results show correlations which describe the relationships between the chosen fluid supply strategy and the maximum resulting process performance, taking into account the energy efficiency of the grinding processes investigated. On the basis of the determined data regarding the energy consumption of the machine tool, the grinding wheel spindle and the fluid supply, a scientifically founded method for the evaluation of the energy efficiency of grinding processes based on the specific energy e_{total} depending on the process parameters and the fluid supply strategy is developed with simultaneous consideration of the process result in terms of surface integrity.

In view of the energy consumption for the fluid supply, the modular nozzle shows higher values for the power consumption compared to the tangential flat nozzle, but the process limits are shifted to higher specific material removal rates which lead to an enhanced energy efficiency. This can be attributed to an enhanced coherency of the fluid jet resulting from the design of the modular nozzle which leads to better cooling and lubrication of the contact zone. In addition, it can be derived from the results for the modular nozzle that also jet speeds higher than the grinding wheel speed lead to an increase in process performance. This is probably caused by an additional cleaning effect by the fluid supply nozzle (simultaneous fluid supply to the contact zone and tool cleaning). For both nozzle designs, the process limit can be increased with a higher fluid flowrate. This contributes to the fact that grinding processes with higher MWF flowrates lead to lower values of the specific energy e_{total} - despite the higher energy consumption for the fluid supply - and are therefore also more energy-efficient. Tool cleaning also has a positive effect on the process performance, but the effect with regard to the specific material removal rate is smaller than expected. Due to the additional energy consumption caused by tool cleaning, energy efficiency is rather reduced despite the positive fact that the degree of clogging is reduced to a minimum.

Future research activities will focus on transferring the developed approach to further grinding processes like finishing processes in combination with the roughing process studied here aiming at the final surface integrity of the part and also to further variations of the fluid supply conditions using 3D-printed nozzles with adapted outlets for profile grinding processes. In addition, the Barkhausen noise measurement only indicates the presence of grinding burn, but also further subsurface properties like e.g. residual stress states need to be considered for describing workpiece quality relevant process limits.

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