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Energy efficiency of state-of-the-art grinding processes

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Abstract

In times of unstable market development due to the energy system transformation and legislative measures concerning the reduction of CO_2 emissions, the manufacturing industry is increasingly aware of the ecological and economical importance of the factor energy. A considerable share of industrial energy and resource consumption can be attributed to machine tools in general and grinding machines in particular. Grinding is an essential technology used for finishing operations of many precision components, especially such made of hard and brittle materials. This work presents an investigation in the energy consumption related to high-performance grinding processes. Grinding tests were performed using different grinding strategies and abrasives including corundum (Al_2O_3) and CBN. In order to identify the dynamic process behavior and energy flows, process parameters were varied and electrical power consumption of the CNC grinding machine, its drive system as well as different peripherals such as cooling lubricant pumps were measured. Specific energy consumption was determined as a function of material removal rate and compared to results of milling and turning processes. The key influence factors on grinding energy efficiency and productivity are depicted. Strategies are evaluated to optimize the overall process performance from an energetic point of view.

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Keywords: Grinding; Machine tool; Energy efficiency; CBN; Cooling lubrication; Sustainable manufacturing; Ecological evaluation

1. Introduction

Grinding is an essential technology especially used for finishing operations of precision components. Especially for hard or brittle materials such as hardened steel and high-performance alloys, high surface quality and dimensional accuracy are difficult or even impossible to realize with other technologies. However, it is a highly energy and resource intensive manufacturing process as it typically requires powerful grinding spindle drive and cooling technologies as well as elaborate auxiliary processes such as grinding fluid processing and mist collection.

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In 2005, U.S. energy consumption due to grinding in manufacturing was estimated to be 17.6 TWh based on assumptions concerning the installed machine capacity and annual production hours [1]. This number may seem overestimated as it corresponds to ca. 1.7% of the total electricity consumption of U.S. industry sector at that time [2]. It is, however, undisputed that the economic and environmental impacts of grinding are substantial. For instance, an LCA investigation of the manufacturing process chain of exemplary engine and powertrain components showed that on average ca. 20% of the resulting global warming potential is attributable to grinding processes [3]. Another study identified that grinding machines had a share of 28% on installed CNC machine tools in the EU-27 in 2009 [4].

When considering the energetic performance of a production system in general and a grinding machine in particular, it is necessary to differentiate between efficiency and effectiveness. Improving the efficiency can be done e.g. by applying new grinding wheel technologies, by utilizing speed-controlled pumps or by employing alternative cooling lubrication technologies in order to reduce the energy demand of a given process. In contrast, an effectiveness approach could make certain process steps obsolete and thus lead to a more drastic decrease in total energy consumption. Different strategies have been identified to reduce energy and resource consumption concerning design and process control of machine tools as well as technological and organizational aspects (cf. [5-10]):

- Selection of the optimal capacity of machine tool and auxiliary systems
- Utilization of more efficient machine tool components (such as drives and pumps)
- Recovery of heat or kinetic energy within the machine tool
- Replacement of integrated by centralized peripherals (or vice versa)
- Selective actuation of non-continuously required devices (such as pumps and ventilators)
- Optimization of process parameters (e.g. by improved design of tool, spindle and machine structure or by utilizing high-performance tool materials) and tool paths
- Optimization of NC-programs and parallelization of processes (e.g. by utilizing multi-spindle machines)
- Alteration of manufacturing technologies (e.g. hybrid processes such as vibration assisted machining)
- Substitution of certain manufacturing technologies (e.g. hard turning instead of grinding or grind-hardening instead of separated hardening and grinding)
- Implementation of automatic machine hibernation during nonproductive times
- Reduction of idle times (e.g. via effective setup and loading strategies as well as production planning measures)

Several studies have been carried out in order to quantify and model the energy demand of machine tools in order to determine their environmental impact [11-13]. These methods were developed for conventional machining processes, essentially taking into consideration constant and process dependent shares of power consumption. In its most rudimentary form, the power consumption of a machine tool is divided in a constant a variable component. Naturally, this is also valid for grinding machines where the (near-)constant share of power consumption (‘base load’) is attributable to components such as drive electronics, cabinet and machine cooling or hydraulics while the dynamic share is typically mainly caused by axes and spindle drives, cooling lubricant supply or mist separation systems.

The processing time is obviously a key influence factor for the energy demand of machine tools, especially such with high base load. Increasing material removal rates lead to a decrease of primary processing time and thus of overall energy consumption [7, 14, 15]. However, decreasing process times may also lead to a higher share of idle times (especially in the case of suboptimal machine utilization) and therefore to a rebound effect concerning total energy consumption. Furthermore, the approach is limited as product dimensional accuracy and surface quality strongly decrease with increasing material removal rates. Li et al. presented an approach to evaluate the interrelationship among process parameters, specific energy consumption and surface roughness for grinding 100Cr6 (62 HRC) using corundum (Al_2O_3) and CBN grinding wheels [16].

Due to its hardness as well as thermal and chemical stability, CBN is utilized for a wide range of precision grinding processes. It enables a combination of high speed grinding and creep-feed grinding, typically referred to as high performance grinding [17]. Especially when employed on high-performance alloys using high cutting velocities, the high costs of CBN are compensated by increased productivity and tool life compared to other abrasives [18]. However, high-performance grinding processes using CBN pose high demands on the grinding machine concerning issues such as spindle stiffness and cooling, dressing and balancing processes as well as cooling lubrication [19].

Neugebauer et al. presented an approach to drastically increase productivity of a camshaft grinding process by using micro-structured CBN grinding wheels enabling optimal cooling lubricant supply [20]. Compared to standard flushing strategies, energy savings of around 20% were achieved and a substitution of flood cooling with minimum quantity lubrication (MQL) was facilitated.

The fact is that in grinding, cooling lubrication is a substantial cost driver. Brinksmeier et al. stated that ca. 17% of the total manufacturing costs for crankshafts at a German automotive manufacturer is attributable to cooling lubrication technology [21]. Thus, one of the most promising ways to reduce energy consumption in grinding would be to decrease or even omit cooling lubrication. Consequently, numerous studies have been published concerning the effects of dry or MQL grinding. Aurich et al., for instance, presented a promising technological approach for high-performance dry grinding using a grinding wheel with defined grain pattern [22]. Oliveira et al. conducted grinding experiments with a CBN wheel using MQL in combination with a compressed air jet for wheel cleaning [23]. Compared to flood cooling and MQL without wheel cleaning, promising results concerning surface quality and wheel wear were obtained. However, the tests were carried out with low cutting speed (30 m/s) and comparatively low material removal rates. The same applies to a comprehensive study presented by Tawakoli et al [24]. They studied the efficiency and performance of different abrasives and cooling lubrication technologies (including dry and wet grinding was well as different MQL strategies) for grinding 100Cr6 (50 HRC). The best results concerning grindability, surface integrity and specific grinding energy were obtained using oil-based MQL.

However, excess heat input to the workpiece, increased tool wear as well as higher thermal and mechanical loading of spindle and machine structure have so far prevented widespread omission of conventional cooling lubricant in grinding. Especially in high performance grinding applications, suitable coolant supply is typically necessary in order to ensure dimensional accuracy and adequate surface quality without thermal damage. In order to obtain optimal results, the cooling lubricant nozzle alignment and cross-section need to be carefully adjusted to the geometric circumstances in the contact zone [25]. Furthermore, the nozzle exit velocity of the coolant jet should be higher than the cutting speed in order to provide a continuous coolant supply into the grinding zone. As the jet velocity c depends on the working pressure p and the pump power consumption P_{el} both on pressure p and volumetric flow $\dot{V}$, powerful (and ideally efficient) pump units are necessary to provide adequate supply (cf. [26]):

$$P_{el} = \frac{\Delta p\, \dot{V}}{\eta} = \frac{\Delta p\, A_{nozzle}\, c}{\eta_{mech}\, \eta_{vol}\, \eta_{hyd}} \approx \frac{p\, {d_{nozzle}}^2\, \pi}{4\, \eta_{mech}\, \eta_{vol}\, \eta_{hyd}} \sqrt{\frac{2\, p}{\rho}} \;\rightarrow\; P_{el} \sim p^{1.5} \tag{1}$$

Denkena et al. showed for milling and drilling that a demand-oriented optimization of coolant flow rates can lead to drastic energy savings without compromising quality and tool wear [27]. This certainly applies to grinding as well.

This work presents the results of an energetic evaluation of a modern CNC grinding machine and different grinding strategies. Energy flows in different operating conditions as well as the characteristic power consumption of different machine components such as the cooling lubrication high-pressure pump or the grinding spindle are determined. The specific energy consumption of different grinding processes is evaluated as a function of process parameters and compared to exemplary machining processes.

2. Experimental setup for grinding tests and power consumption measurement

In order to identify the energy consumption of state-of-the-art grinding processes, grinding tests were performed on a 'GST FSM 400-200 HIGH SPEED' horizontal-surface CNC grinding machine. The machine features a 35 kW main spindle for speeds up to 10 000 rpm, a linear motor driven x-axis for feed rates of up to 200 m/min and two high-pressure cooling lubricant pumps (18.5 kW for cooling lubrication and 11 kW for wheel cleaning). Concurrent speed-stroke and creep-feed pendulum grinding was performed on two materials (carbon steel and hardened cold-work steel) with different grinding wheel technologies (standard and high-performance Al_2O_3 for cutting velocities of up to 40 and 100 m/s, respectively, as well as CBN). Synthetic emulsion (Blaser Synergy 915) with a concentration of ca. 6% was employed as cooling lubricant. It was supplied to the wheel via two flat-jet nozzles, one tangential (supplying the contact zone) and one radial (for wheel cleaning, see Figure 1, left), with a pressure of 50 bar and a nozzle gap of 0.3 mm. Dressing was performed using a rotary CNC dressing disc (see Figure 1, right).

Electrical power consumption of the whole machine, the drive system and different peripherals (such as cooling lubricant pumps, machine cooling system and mist separator) was measured and recorded with a temporal resolution of 100 ms using power monitoring devices and an Ethernet based data acquisition system.

Compressed air consumption was quantified as about 1.2 Nm³/min during processing and 0.4 Nm³/min (at 6 bar) in 'operational' condition (cf. [28]) and is attributable mainly to sealing air applications (spindle, glass scales).

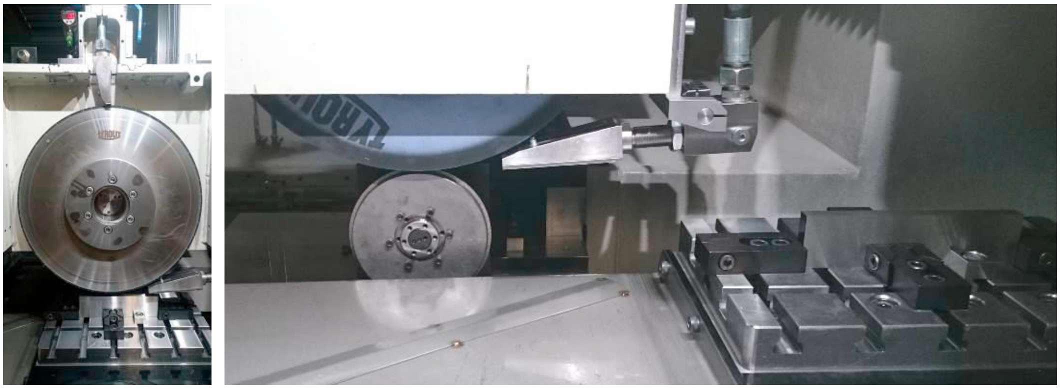

Figure 1. Setup for the grinding tests with CBN steel wheel (left) and with Al_2O_3 wheel in dressing position (right)

Figure 2 shows the dynamic energetic behaviour of the grinding spindle and the cooling lubricant high-pressure pump. The left graph shows the dependence of spindle idle power consumption on spindle speed in different conditions. With grinding wheel, spindle power consumption is significantly higher than without which is mainly attributable to aerodynamic drag (which has a quadratic relationship with speed). With activated cooling lubrication, spindle power decreases at low speeds due to positive relative velocity in relation to the coolant jet (and thus positive force effect). At higher speeds, however, power consumption increases strongly, presumably also due to drag effects. The second graph in Figure 2 shows the dependency of peak power during spindle acceleration from standstill to set speed. Naturally, the power peak is higher and the acceleration time longer when accelerating higher masses (CBN steel wheel: 16.6 kg, Al_2O_3 wheel: 5.3 kg). The right graph shows the dependence of pump power consumption on cooling lubricant pressure (for a constant nozzle gap) which is in good agreement with the relationship in equation 1.

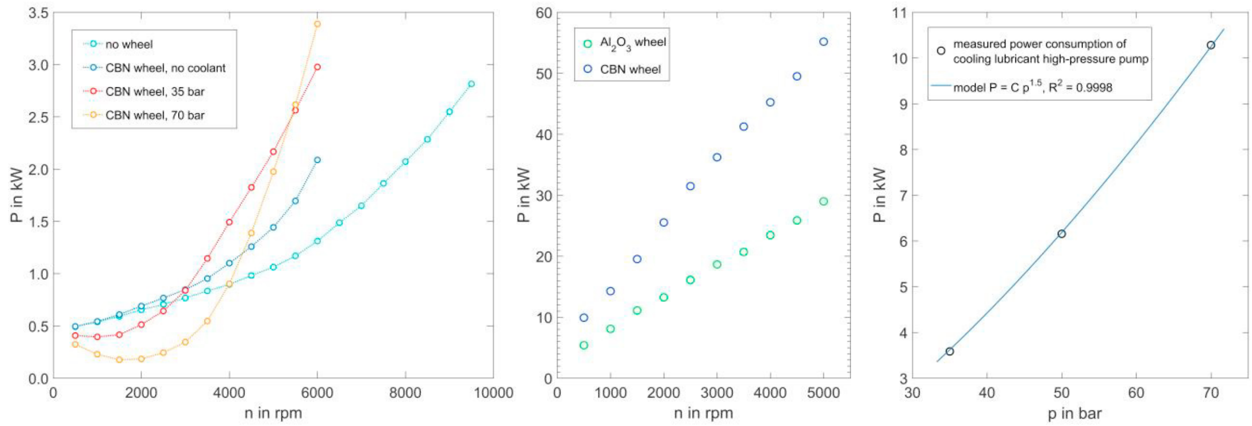

Figure 2: Spindle idle power consumption (left), spindle acceleration power peak (middle) and HD pump power consumption (right)

The consumption behaviour of the grinding machine was determined in all relevant operating conditions according to ISO/DIS 14955-2 [29]. Figure 3 shows the average power consumption of the machine in two representative operating conditions. The cooling lubricant recirculation pump and the machine cooling compressor are activated on demand (i.e. according to level and temperature control, respectively), the mist separator is turned on during processing and a certain follow-up time and bed flushing is activated manually. The speed-controlled high-pressure pumps are controlled individually and were activated on 50 bar pressure stage during feed motion in the grinding tests.

In the grinding tests, cutting speed v_c, feed rate v_w and cutting depth a_e were varied according to Table 1 in order to achieve different specific material removal rate values ($Q'_w = v_w\ a_e$) while maintaining good workpiece quality throughout all tests (no grinding burn, average roughness Ra < 1 µm normal to grinding direction). The process parameters were either chosen according to grinding wheel manufacturer specifications or to technological limits.

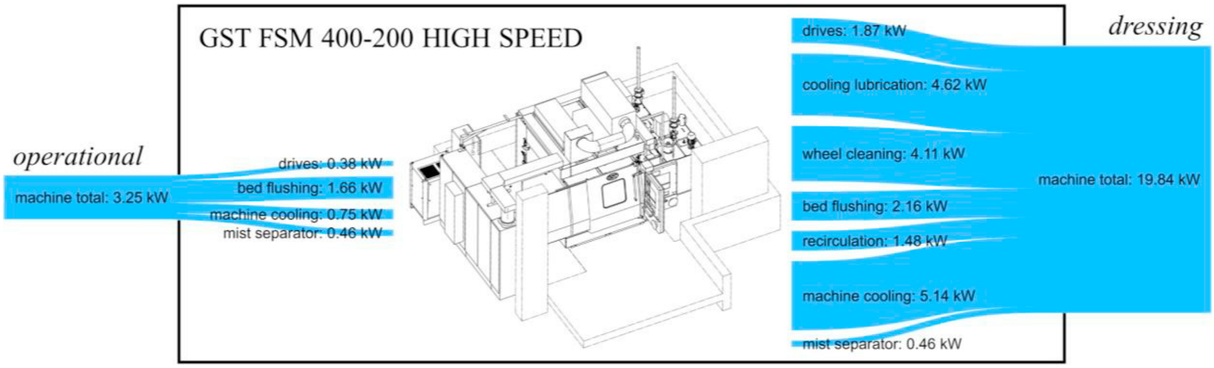

Figure 3. Electrical power consumption of the grinding machine in 'operational' condition (left) and during dressing (right).

Table 1. Process parameters for grinding tests.

workpiece material	abrasive	v_c [m/s]	v_w [m/min]	a_e [mm]	a_p [mm]
1.1191 (46 HRC)	Al_2O_3 (40 m/s)	25, 35, 35, 40	15	0.02, 0.04, 0.06, 0.08	16
1.2510 (62 HRC)	Al_2O_3 (100 m/s)	55, 70, 85, 100	50, 100, 150, 200	0.002	8
1.2510 (62 HRC)	CBN	50, 75, 100, 125	0.6, 1.2, 1.8, 2.4, 3.0	0.5	8

The left graph in Figure 4 shows the electrical power signals for one stroke of creep-feed grinding (i.e. high a_e and low v_w with Q'_w = 20 mm³/mm/s) using a CBN grinding wheel. Power is plotted logarithmically in order to enhance the distinguishability of the individual signals. From the drive power consumption signal, several process stages can be identified, i.e. spindle drive acceleration (at ≈ 1.5 s), feed drive acceleration (≈ 3 s) and tool engagement (starting at ≈ 7 s and lasting for ≈ 4.5 s). The right graph shows the situation for ten strokes of speed-stroke grinding (i.e. low a_e and high v_w with Q'_w = 6.67 mm³/mm/s) using high-performance Al_2O_3. Acceleration and deceleration peaks of each stroke can be identified from the drive power signal. However, due to the high velocity and thus short tool engagement times, it is not possible to distinguish tool engagement. The higher total power consumption of the creep-feed grinding process is attributable to the slightly higher cutting speed and the activated recirculation pump. The higher spindle acceleration power peak and longer acceleration time can be explained by the higher weight of the CBN wheel and the higher cutting speed (cf. Figure 2, center). In both cases the cooling compressor was inactive.

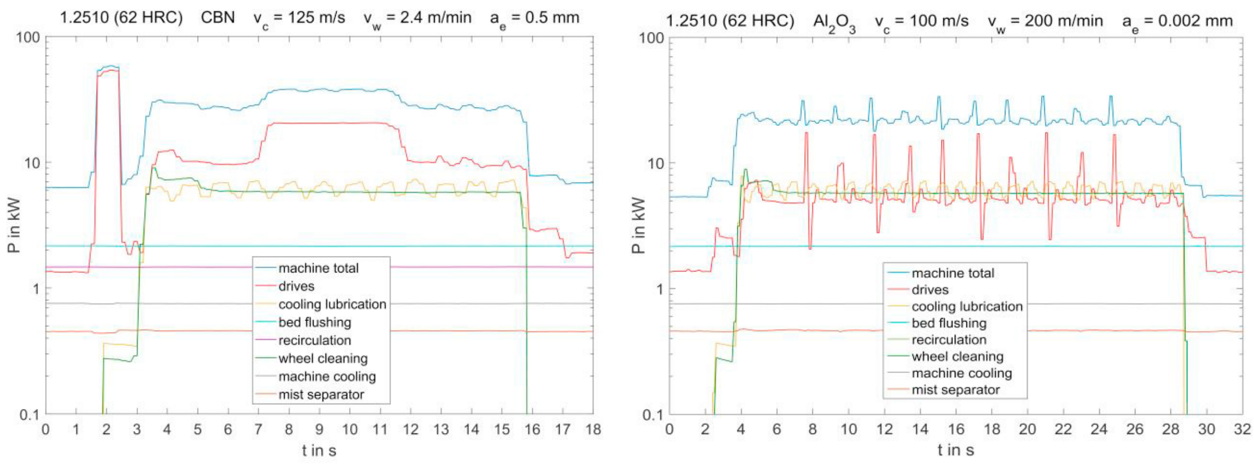

Figure 4. Electrical power consumption of the grinding machine and different peripherals during creep-feed grinding (1 stroke, left) and speed-stroke grinding (10 strokes, right).

3. Specific energy consumption and energy efficiency

The average process power $\overline{P_P}$ during grinding corresponds to the spindle power in loaded condition subtracted by the spindle idle power at the same speed (cf. [30-31]):

$$\overline{P_P} = \overline{P_{loaded}} - P_{idle} \tag{2}$$

For the creep-feed grinding process shown in Figure 4 (left), the average process power during tool engagement is 10.84 kW. This results in an energetic process efficiency η_P of 29% during grinding and 13.5% for the whole process:

$$\eta_P = \frac{\overline{P_P}}{\overline{P_{tot}}} \tag{3}$$

Neglecting positioning, spark out, balancing and dressing processes, the total specific energy consumption e is determined by setting the total energy consumption E_{tot} in relation to the removed material V_w:

$$e = \frac{E_{tot}}{V_w} = \frac{\int P_{tot}\, dt}{V_w} = \frac{\overline{P_{tot}}\, t_P}{a_e\, a_p\, l} = \frac{e_P}{\eta_P} \tag{4}$$

Figure 5 shows the influence of specific material removal rate Q'_w and cutting speed v_c on the specific energy consumption e and the energetic process efficiency η_P of the creep-feed grinding process. Naturally, e increases with increasing v_c as drive power consumption rises with spindle speed (cf. Figure 2, left). Increasing Q'_w, on the other hand, leads to strongly decreasing e which is due to reduced processing time and thus reduced energy consumption in particular of peripherals (cf. [14]). The shown process efficiency values were determined from values averaged over the whole process (i.e. not only during tool engagement) according to equation 3. The highest efficiency values occur for the highest values of Q'_w and v_c which is attributable to the fact that the cutting force (and thus process power) rises with increasing feed rate and cutting speed.

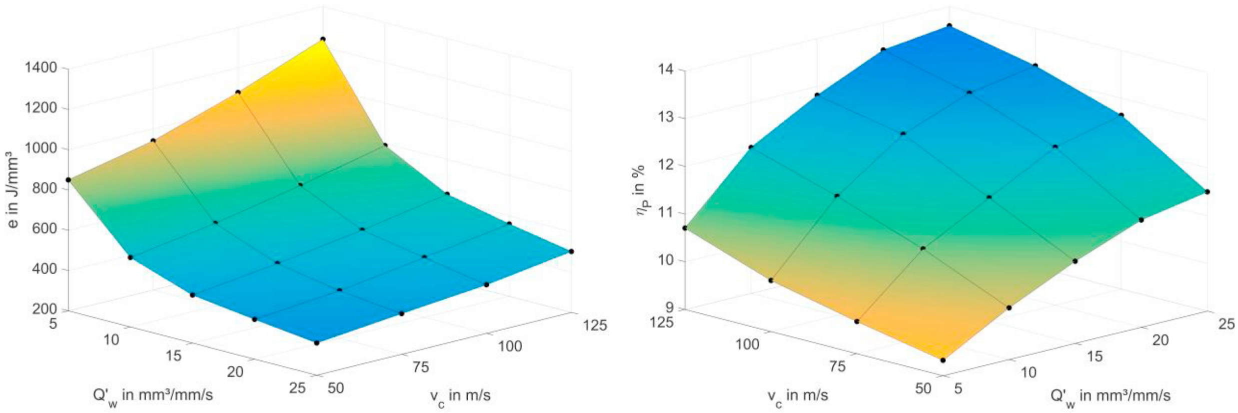

Figure 5. Dependence of specific energy consumption e (left) and energetic process efficiency η_P (right) on cutting speed and specific material removal rate for creep-feed grinding 1.2510 (62 HRC) using CBN.

The specific energy consumption can be modelled according to equation 5. The model shows good agreement to the measured data for the material and process parameters of the given creep-feed and speed-stroke grinding processes (see Table 3) and is, to a certain extent, of general application in machining (cf. [5, 7, 32]).

$$e = C_1 + \frac{C_2}{Q'_w} + C_3\, v_c \tag{5}$$

Table 2. Coefficients of modelled specific energy consumption $e = C_1 + C_2/Q'_w + C_3\, v_c$ (in J/mm³).

process	C_1	C_2	C_3	R^2
creep-feed grinding (CBN)	18.59	3730.47	3.00	0.9780
speed-stroke grinding (Al_2O_3 100 m/s)	12504.84	7956.85	65.57	0.9845

For the same specific material removal rate and material, specific energy consumption is around 20 times higher for speed-stroke grinding compared to creep-feed grinding (see Figure 6, left). This is due to the limited cutting depth attainable with Al_2O_3. Despite the fast feed rate (v_w = 200 m/min), the time to remove the same material volume compared to creep-feed grinding is much longer. Thus, the effect of (partly process independent) energy consumption of peripherals is much stronger than the reduced process energy. In comparison, the speed-stroke grinding process of the standard carbon steel shows the lowest energy intensity which is attributable to much lower process energies (due to the lower material strength) and higher feed rates compared to creep-feed grinding as well as much higher cutting depth compared to speed-stroke grinding of hardened cold-work steel.

These specific energy requirements for grinding ranging from around 300 to 12 000 J/mm³ are comparatively high compared to machining processes like turning or milling where typical values lie in the order of magnitude of 1 to 100 J/mm³ (obviously depending on technological and process parameters as well as machined material, cf. [33]).

The right graph in Figure 6 shows the resulting specific energy consumption of the investigated grinding processes compared to that of the machining processes performed on conventional machine tools (cf. Table 3). In order to allow a comparison of the different processes, the specific energy was set in relation to the material removal rate Q_w (grinding/milling: $Q_w = v_w\ a_e\ a_p = f\ n\ a_e\ a_p$, turning: $Q_w = v_c\ f\ a_p$).

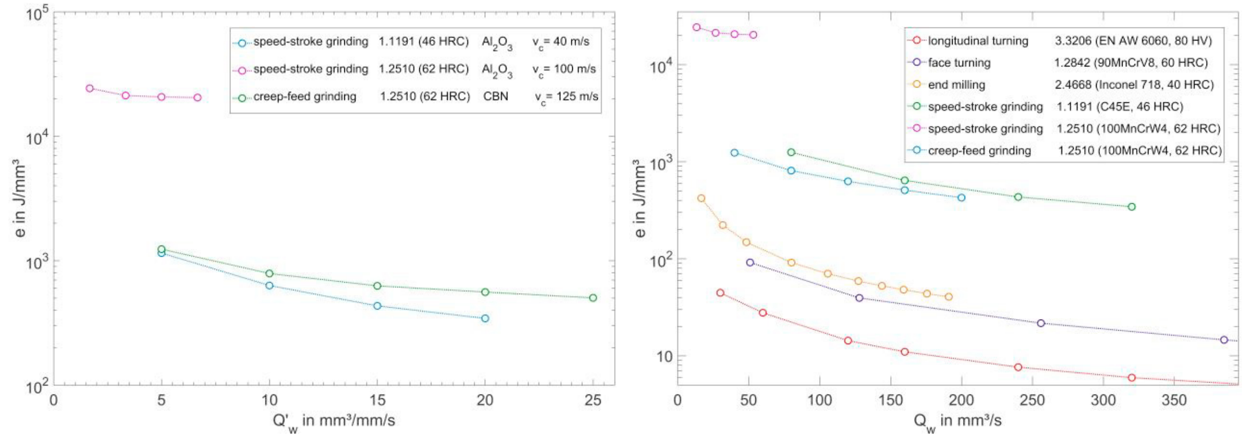

Figure 6. Dependence of specific energy consumption on specific material removal rate for three grinding processes (left) and on material removal rate for the same grinding processes compared to conventional machining processes (right).

4. Summary and conclusions

The electrical power consumption of the investigated CNC grinding machine during dressing is attributable mainly to cooling lubricant pumps (44% for high-pressure pumps, 62% in total), machine cooling (26%) and the drive system (9%). The power consumption of high-pressure pumps greatly depends on the target pressure for which reason demand-oriented adjustment of cooling lubricant flow rates is a highly effective way to increase energy efficiency.

Typically, demand-oriented control of low-pressure cooling lubricant supply (such as for rinsing), compressed air supply or mist separation offers great energy-saving potentials (especially in series production) as well. When reducing cooling lubricant consumption, a positive side effect is that not only pump power consumption decreases but also the heat input to the fluid and thus the energy required for recooling it.

Specific energy consumption during grinding is inversely proportional to the material removal rate and linearly proportional to the cutting speed. For the same workpiece material and cooling lubrication strategy, the investigated speed-stroke grinding process using Al_2O_3 shows around 20 times higher specific energy consumption as creep-feed grinding using CBN. This is attributable to technological limitations concerning cutting depth and velocity and thus longer process times.

For the given process parameters and material, the energetic process efficiency (i.e. the share of machine total power consumption used for material removal) during creep-feed grinding with CBN reached values of up to 32%. Thus, the application of CBN allows for the realization of comparatively productive and efficient grinding processes.

The specific energy consumption of heavy-duty grinding processes can reach the same order of magnitude or even lower values as a finishing process in machining (especially on powerful machine tools with large peripherals). However, high-performance dry machining processes (especially of low-strength materials) offer about 10^4 times higher energy efficiency than grinding processes with small cutting depth. This is mostly due to elaborate and energy intensive auxiliary processes necessary to provide grinding process stability, in particular cooling lubrication and spindle cooling. For this reason, high attention should be paid in machine and process design not only to workpiece quality (which is often the only design criterion), but also energy and resource efficiency and thus, indirectly, productivity.

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