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HIGHER COMPETITIVENESS OF SPEED-STROKE GRINDING BY USING INCREASED WHEEL SPEEDS

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ABSTRACT

Production engineering faces the challenge to satisfy the increasing industrial demand for higher productivity and high requirements on workpiece quality at the same time. Furthermore, the rising environmental awareness adds additional constraints. Especially grinding processes have high relevance for industrial applications because they generate high quality surfaces and they are most effective for hard-to-machine materials. New technologies like speed-stroke grinding and high cutting speeds enable higher productivity. However, to be competitive to conventional grinding operations energy aspects have to be regarded thoroughly. This work shows how the combination of speed-stroke grinding and high speed machining can boost process performance, workpiece quality and process sustainability.

INTRODUCTION

Only producing high quality products with ongoing time and cost optimization can lead to success in the global industrial competition. For continuous improvement, producers have to enhance process chains and single manufacturing steps. Especially grinding processes have high relevance because they generate high-end surfaces or are effective removal techniques for hard-to-machine materials. The technology of speed-stroke grinding represents a promising alternative to conventional grinding strategies. Increased table speeds of up to v_w = 200 m/min can minimize the machining times and costs as well as improve the component quality.

ACTIVE MECHANISMS IN GRINDING

A. *General considerations*

In the past, grinding was regarded to be only a finishing process at the end of the process chain. But nowadays abrasive machining offers also high potential for high performance machining [1]. During grinding processes, thermal and mechanical effects arise; they superimpose and affect the surface integrity dominantly. The main kinematic process parameters in surface grinding as table speed v_w, depth of cut a_e and grinding wheel velocity v_s have a high influence on the thermal and mechanical effects [2]. This work focuses on these kinematical parameters and on the resulting maximum undeformed chip thickness $h_{cu,max}$, which all have an explanation for most of the fundamental effects [3, 4, 5, 6 and 7], seen in (equation (1)).

$$h_{cu,max} = c_{gw} \cdot \left(\frac{v_w}{v_s}\right)^{e_1} \cdot \left(\frac{a_e}{d_{eq}}\right)^{\frac{e_1}{2}} \quad (1)$$

Here, c_{gw} is the constant for the grinding wheel topography, d_{eq} is the equivalent grinding wheel diameter and e_1 is an exponent, which describes the influence of the input parameter within the brackets. The grinding wheel velocity, as one parameter to focus on, changes the maximum undeformed chip thickness while all other parameters are kept constant. An increasing grinding wheel velocity leads to decreasing chip thickness which results in reduced grinding force and improved part surface quality. Moreover, the radial grinding wheel wear decreases and will extend the grinding wheel life, which is positive regarding resource efficiency. An increasing table speed results in rising maximum undeformed chip thickness. Moreover, with higher table speed, the number of active cutting grains increases, whereas the momentary number of cutting grains $\overline{N}_{mom}$ decreases [8] (equation (2)). Therefore, the force load per single grit increases leading to possible grit break outs and bond breakage.

$$\overline{N}_{mom} \approx v_w^{-\frac{1}{3}} \qquad (2)$$

The combination of the parameters table speed and depth of cut yields the specific material removal rate Q'_w (equation (3)). This value is important to compare different processes concerning their efficiency.

$$Q'_w = a_e \cdot v_w \qquad (3)$$

When the specific material removal rate is held constant, both parameters depth of cut and table speed have to be changed. Since the table speed affects the maximum undeformed chip thickness stronger than the depth of cut, seen in (1), the chip thickness will increase with increasing table speeds.

B. Combination of high table and high cutting speeds

This section combines the state of the art process variants speed-stroke grinding and high speed grinding in theory. The speed-stroke grinding process was advanced at the Laboratory of Machine Tools and Production Engineering (WZL) at the RWTH Aachen University with table speeds up to $v_w = 200$ m/min and accelerations with values up to $a_w = 50$ m/s² [8, 9]. Zeppenfeld investigated the technological principles of chip formation and wear mechanisms for increasing table speeds when grinding γ-titanium aluminides whereas Nachmani researched the mechanical and thermal influence separately for quenched and tempered steel with conventional grinding wheels in speed-stroke grinding.

Both authors showed the advantage for grinding with high table speeds. For example, the mechanisms of chip formation are changed with increasing table speeds because of the increasing maximum undeformed chip thickness. Therefore, the proportion of the elastically and plastically deformation diminishes in favor of earlier chip removal. Friction processes at the grit are reduced resulting in lower heat generation. Furthermore, grinding with high table speed reduces the contact time inhibiting the heat dissipation into the surface layer. Thermal damage can be avoided by speed-stroke grinding. Moreover, the overall energy consumption takes the machine tool concept into account.

For high speed grinding, i.e. high grinding wheel velocities, different authors showed the positive influence on the surface integrity [1, 10, 11 and 12]. Because the maximum undeformed chip thickness will decrease with increasing grinding wheel velocity, the grinding force will decrease as well as the radial grinding wheel wear. Ferlemann investigated grinding wheel velocities up to $v_s = 500$ m/s with a galvanic bonded CBN (cubic boron nitride) grinding wheel and showed an optimum operating point at $v_s = 220$ m/s in terms of low grinding forces and power [11]. However, in practical application the grinding wheel velocity differs between $v_s = 60$ up to 200 m/s.

Recently, Oliveira et al. figured out actual trends for commonly used grinding wheel velocities in the grinding machine industry [13]. Specified for CBN grinding wheels, only 13 % of the surveyed 23 manufactures use mainly grinding wheel velocities up to 200 m/s. The major reasons for the comparably low proportion of high wheel speeds are the complex machines with additional systems as well as economical reasons. However, the competitiveness of processes includes productivity, quality and resources. So the low usage of high speed grinding is noteworthy in the face of the discussed obvious advantages of reduced chip thicknesses. It is expected that the enhanced process performance by high speed machining can lead to higher resource and energy efficiency. The hypothesis of this paper claims that the combination of speed-stroke and high speed grinding leads to higher material removal rates with constant quality properties. Reduced tensile residual stresses even could enhance the product functionality leading to longer product life and less environmental impact.

EXPERIMENTAL SETUP

The third step includes experimental validation of the hypothesis with grinding tests on a speed-stroke grinding machine Blohm Profimat MT 408 HTS. Quenched and tempered steel (AISI 52100, HRC 62±3) was machined with vitrified bonded CBN (B181 LHV 160) grinding wheels for both increasing table speeds and grinding wheel velocities. CBN grinding tools have higher wear resistance resulting in reduced waste. Due to the higher thermal conductivity, positive compressive stresses can be added to the workpiece surface. Nevertheless, these tools are much more expensive than conventional tools and designed for high wheel velocities, i.e. high spindle power, to achieve their advantages. Therefore, the proper process window is crucial for a sustainable usage of CBN abrasive tools. During the grinding tests, the relevant process parameters were systematically varied with a maximum specific material removal of $V'_w = 1{,}000$ mm³/mm. The specific material removal rate was increased from $Q'_w = 10$ mm³/mms up to 40 mm³/mms. Furthermore, the table speed was increased from $v_w = 12$ m/min up to 180 m/min, whereas the grinding wheel velocity was varied from $v_s = 80$ m/s up to

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160 m/s. A simultaneous change of grinding wheel velocity and workpiece speed nearly kept the chip thickness constant whereas the specific material removal rate is increasing.

In order to measure grinding forces a 3-Component-Dynamometer including a piezo-electric force transducer from Kistler was used. The grinding wheel wear was measured against an unworn tool area from replica plates with the same tactile stylus method that was used for the workpiece roughness. The residual stress in the workpiece material was identified with X-ray diffraction.

ADVANTAGES OF SPEED-STROKE AND HIGH SPEED GRINDING

A. *Specific grinding energies*

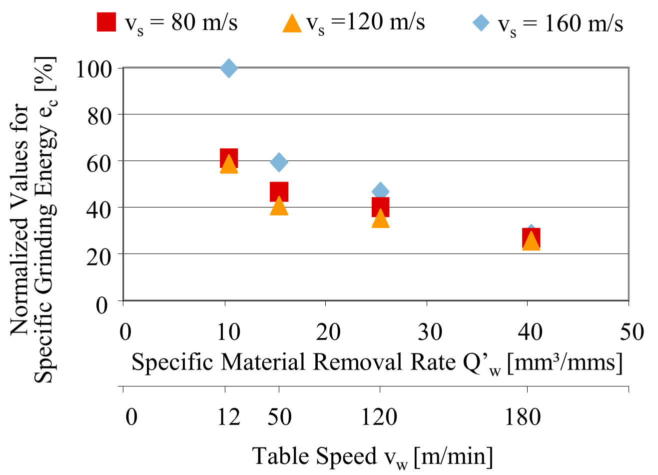
We define the specific grinding energy as energy used to machine one volumetric unit of material. The specific grinding energy changes with the active mechanisms in chip formation. As derived theoretically the specific grinding energy should decrease with rising table speed due to the decreasing momentary number of cutting grains. Moreover, an increase of the chip thickness leads to a reduction of the elastic and plastic phase before the chip is formed in the grinding zone and reduces also the specific grinding energy. From measured tangential grinding forces F_t, the specific grinding energy e_c can be deducted, as seen in equation (4) [14].

$$e_c = \frac{F_t \cdot v_s}{Q'_w} \tag{4}$$

Fig. 1 shows the specific grinding energy for the grinding wheel velocities of $v_s = 80$ m/s, 120 m/s and 160 m/s and different specific material removal rates Q'_w. All values are related to the reference value of 100 % for a grinding wheel velocity of $v_s = 160$ m/s and a table speed of $v_w = 12$ m/min. In this diagram, the reference value is also the maximum value.

The specific material removal rate, defined by the multiplication of depth of cut and table speed (equation (3)), was increased by variation of both parameters. With increasing material removal rate the specific grinding energy was reduced, which is known from other research as well [8, 9]. At $v_w = 180$ m/min the specific grinding energy was only 30 % of the initial value at a table speed of $v_w = 12$ m/min and a grinding wheel velocity of $v_s = 160$ m/s. This was caused by the increasing chip thickness (equation (1)) and therefore the alteration in chip formation with higher table speeds, even if the depth of cut was reduced. The table speed has a higher influence on the chip thickness than the depth of cut. With thicker chips the phases of elastic and plastic deformation diminished against the phase of chip formation increasing the machining efficiency.

With similar mechanisms the grinding energies are decreasing with lower grinding wheel velocities because a lower number of grits was engaged and the chip thickness grew. However, the difference of grinding energies for the three examined grinding wheel velocities was predominant for small specific material removal rates (up to 40 %) and could be neglected for $Q'_w = 40$ mm³/mms.



Grinding wheel	Parameter	Dressing parameter
B181 LHV 160	$V'_w = 1000$ mm³/mm	$U_d = 4$
Material	**Coolant**	$q_d = 0.6$-0.8
100Cr6 (HRC 62)	Emulsion (5%)	$a_{ed} = 3$ µm

Figure 1. Proportional values for the specifc grinding energy in dependency of different grinding wheel velocities

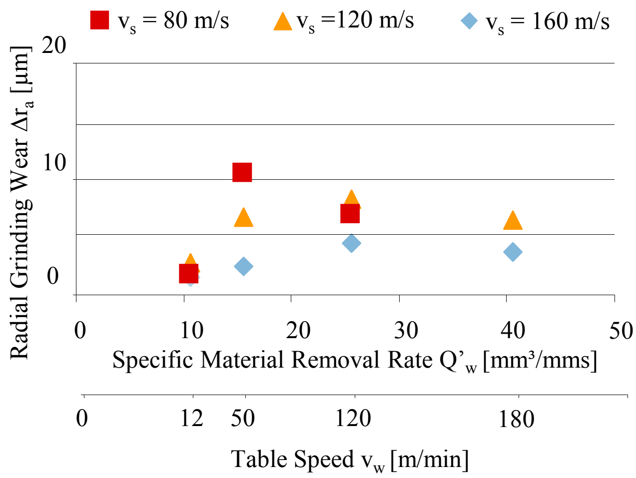
B. *Wheel wear and process costs*

The process efficiency is defined by the process outcome and the used resources as the grinding tool as well as machine and labor time.

The radial grinding wheel wear was lower than $\Delta r_a = 10$ µm for a specific material removal of $V'_w = 1{,}000$ mm³/mm being within the domain of uncertainty (Fig. 2). At a value of $Q'_w = 40$ mm³/mms the grinding wheel wear for the lowest grinding wheel velocity of $v_s = 80$ m/s point out of the tolerance and therefore is not shown in the diagram. Here the wheel wore by break out of whole grits from the bonding system. The highest undeformed chip thickness was reached for this set of parameters leading to a high mechanical load on the tool. Although, the grinding process might profit from high chip thicknesses with a small thermal load on the surface layer, however, the tool life costs would be prominent for these parameters. Moreover, the geometrical machining accuracy would be harder to obtain.

Apart from the high grinding wheel wear at $Q'_w = 40$ mm³/mms and $v_s = 80$ m/s, the tool life was similar and did not affect process costs remarkable. Therefore, the process costs by machining time and used grinding power from equation (5) gain even more interest.

$$P_c = F_t \cdot v_c \tag{5}$$

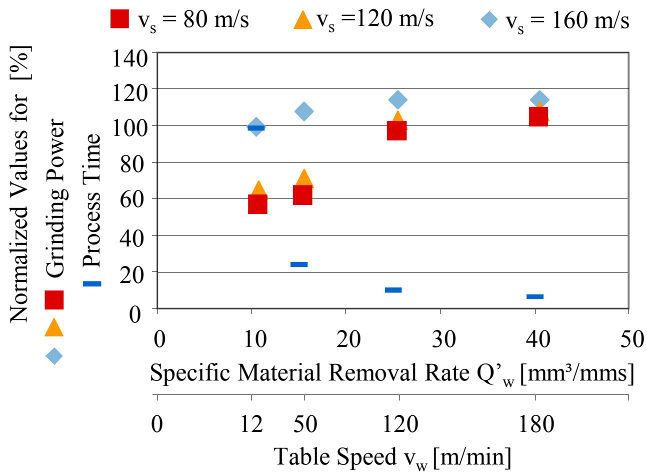


Grinding wheel	Parameter	Dressing parameter
B181 LHV 160	V'_w = 1000 mm³/mm	$U_d = 4$
Material	**Coolant**	q_d = 0.6-0.8
100Cr6 (HRC 62)	Emulsion (5%)	a_{ed} = 3 µm

Figure 2. Radial grinding wear in dependency of the table speeds and the grinding wheel veloceties

In Fig 3 normalized values are given where the reference value for 100% is set by a grinding wheel velocity of v_s = 160 m/s and a table speed of v_w = 12 m/min. The grinding process time simply decreased reciprocally with increasing material removal rate (Fig. 3). In contrast, the grinding power P_c rose with higher specific material removal rates and higher grinding wheel velocities. However, as the grinding time decreased faster than the grinding power P_c increased the used total energy for grinding with a specific material removal was smaller. For example at Q'_w = 40 mm³/mms the time was reduced by 93 % of the value for Q'_w = 10 mm³/mms, but the grinding power increased only by 17 % for a grinding wheel velocity of v_s = 160 m/s. This confirmed the findings of Denkena et al. [15]. At higher specific material removal rates up to Q'_w = 40 mm³/mms the grinding wheel velocities barely affected the grinding power.

The environmental performance of manufacturing systems can be significantly improved by reducing the energy consumption of machine tools [16]. However, the total power consumed by a machine tool sums up by idle power of spindles, axes and periphery and the specific machining power which varies with the process parameters. The specific cutting energy accounts only for a minor part of the total energy consumed [17-19]. Thus, the argument of time reduction with lower increase of grinding power strikes even more.



Grinding wheel	Parameter	Dressing parameter
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Material	**Coolant**	q_d = 0.6-0.8
100Cr6 (HRC 62)	Emulsion (5%)	a_{ed} = 3 µm

Figure 3. Proportional values for the grinding power in dependency of different grinding wheel velocities

C. Surface integrity and surface roughness

The surface layer properties of the workpiece, such as residual stresses and surface roughness, are vital factors in the quality of the component and must be considered when choosing process parameters. Theoretically, the thermal impact will increase with higher grinding wheel velocities due to the increasing number of active cutting grains. Hence, more grit engagements occur resulting in friction. With simultaneously accelerated table speeds, however, fewer grits are engaged within the grinding zone for the same time period. This will result in less energy needed to form the chip.

The speed-stroke grinding process was also investigated in 2D FEM models [20] and 3D FEM models with temperature-dependent material properties and heat source profiles derived from experimental results [21]. Good agreements between the FEM simulations and measured temperatures during grinding processes could be accomplished [20, 21]. The increased table speeds in speed-stroke grinding reduced surface temperatures remarkably.

In support of this theory, Nachmani detected that tensile residual stresses in the surface layer of quenched and tempered steel (1.7225) decreased when the table speed was increased and the removal rate kept constant [9]. This supports the idea that residual stresses are dominated by thermal effects for low table speeds, as seen in Fig. 4 [22].

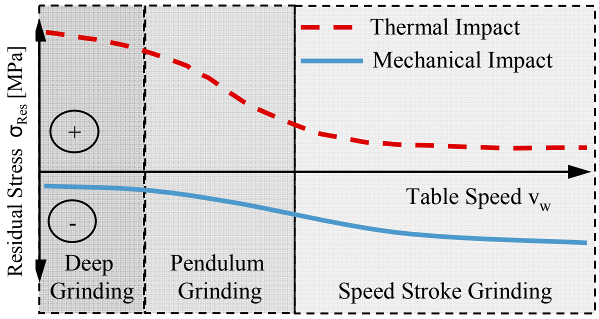


Figure 4. Residual stress model for speed-stroke grinding of quenched and tempered steel with CBN-grinding wheels [22]

In comparison to Nachmani [9], where conventional corundum tools were used, compressive residual stresses were measured after grinding with CBN grinding wheels at low table speeds [22, 23]. Also the difference between conventional abrasives and superabrasives was reported several times in the literature. For example, [24] found compressive residual stresses when grinding bearing steel with CBN grinding wheels, whereas harmful tensile residual stresses were easily formed with aluminum oxide wheels. One reason is the comparatively much higher thermal conductivity of CBN compared to corundum. This leads to relatively lower heat in the chip formation zone for CBN grinding tools [2]. The thermal influence on the surface layer is reduced whereas the mechanical impact increases, which results in lower tensile or even compressive residual stresses.

Moreover, with decreasing specific grinding energy (Fig. 1) compressive residual stresses can be induced at the surface layer for e.g. the specific material removal rate of $Q'_w = 10$ mm³/mms, as seen in Fig. 5.

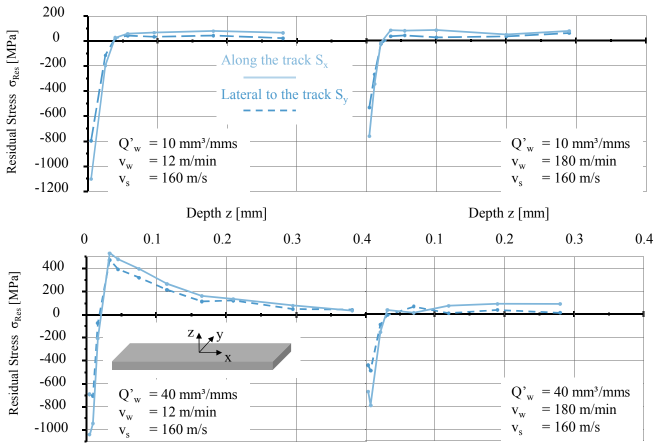
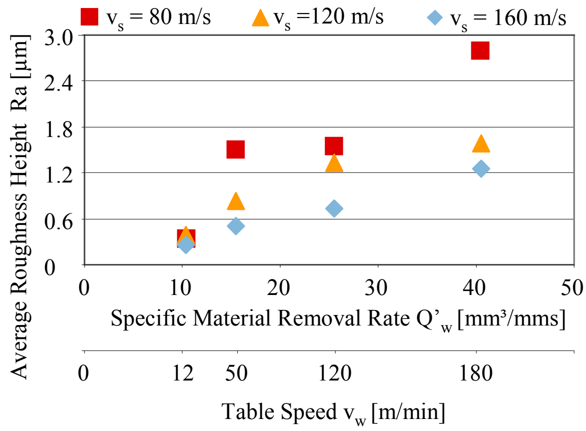


Figure 5. Residual stress measurement for different table speeds

On the other hand, after grinding with the high specific material removal rate of $Q'_w = 40$ mm³/mms and the low table speed of v_w = 12 m/min tensile residual stresses occur in the surface layer. However, the compressive residual stresses near to the surface lead to the assumption that the surface layer had been austenitized and the material volume had increased. Nevertheless, if the high $Q'_w = 40$ mm³/mms was applied at a high table speed of v_w = 180 m/min and small depth of cut accordingly, the residual stresses were less pronounced. This is more favorable and diminishes the danger of crack initiation.

Fig. 6 shows the average surface roughness height increasing with higher table speeds. For higher wheel speeds the roughness heights decreased. Both effects are explained by the undeformed chip thickness according to equation (1). Even for the high specific material removal rate of $Q'_w = 40$ mm³/mms using high wheel speed of v_s = 160 m/s reasonable surface roughness can be expected.



Grinding wheel	Parameter	Dressing parameter
B181 LHV 160	V'_w = 1000 mm³/mm	$U_d = 4$
Material	**Coolant**	q_d = 0.6-0.8
100Cr6 (HRC 62)	Emulsion (5%)	a_{ed} = 3 µm

Figure 6. Average roughness height in dependency of different grinding wheel velocities

ENVIRONMENTAL LIFE CYCLE ASSESSMENT OF SPEED STROKE GRINDING

Grinding is a very complex manufacturing process with a large number of quantities influencing each other, and the reproducibility is critical [13]. This is a challenge for describing and analyzing the process to assess environmental aspects. Fig. 7 shows a comprehensive diagram on the input and output streams to the grinding process, which can be used for a Life Cycle Inventory to assess the environmental impact of a specific grinding process. In our analysis, we included the items: tooling, processing energy (specific grinding energy), surface roughness and surface integrity, all marked in bold. A holistic Life Cycle description of the speed stroke grinding process would enclose all items mentioned and compare their dominance by sensitivity analysis. This holistic description is aim of future research.

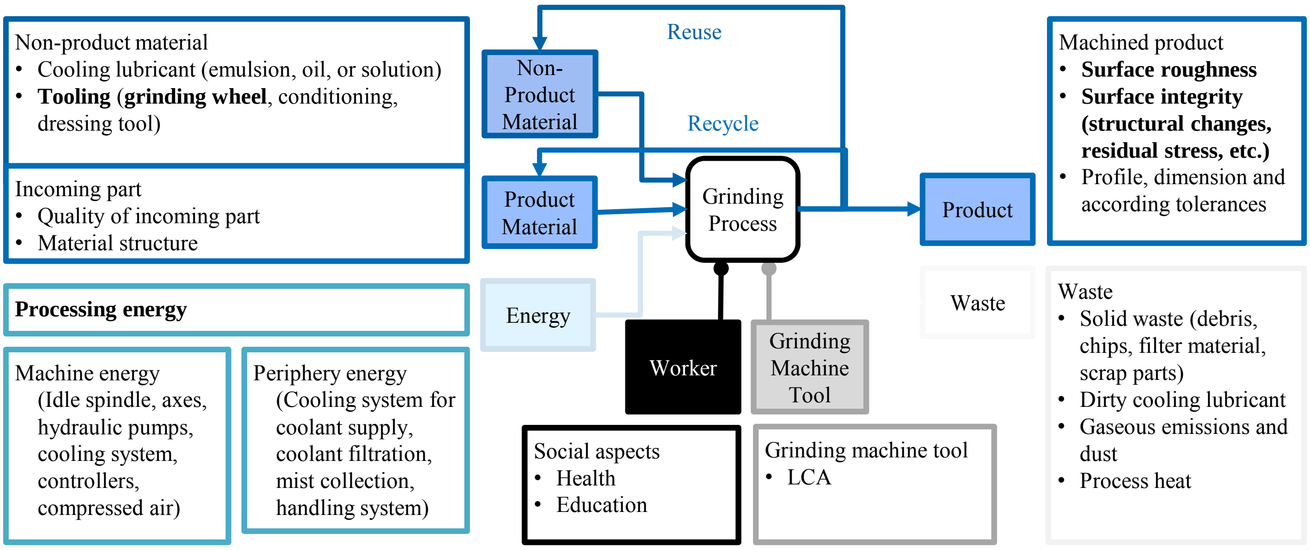


Figure 7. Comprehensive input-output diagram of a grinding process with analyzed items in bold, after [30]

ENHANCED PRODUCT LIFE

The examined speed stroke grinding procedures produced low tensile or compressive residual stresses near the product surface. For the relevant cases with high wheel speeds, the surface roughness was of sufficient quality. Residual stresses in particular affect the rolling contact fatigue life through both mechanisms, changing the crack initiation life and the crack propagation life [28]. Fatigue characteristics are a prime consideration in determining component failure under dynamic loading and cyclical stresses [29]. Small tensile or compressive residual stresses are therefore desirable for low crack propagation, especially at cyclic load. Often these characteristics are produced by a subsequent manufacturing process, such as shot peening or roller burnishing. However, if the grinding process itself generates the desired surface integrity, the process chain will be shortened and efforts will be saved.

One application for speed stroke grinding with high wheel speeds is producing bearing components such as guideways. Herein, the surface integrity of guideways defines their functionality significantly. Jawahir et al. point out the high importance of surface integrity from an industrial perspective, especially where safety is paramount, but also with high cost products [29].

Following the fact that the manufacturing process parameters affect surface integrity which defines part function [29], Fig. 8 visualizes the case study of speed stroke grinding of a machine tool guideway.

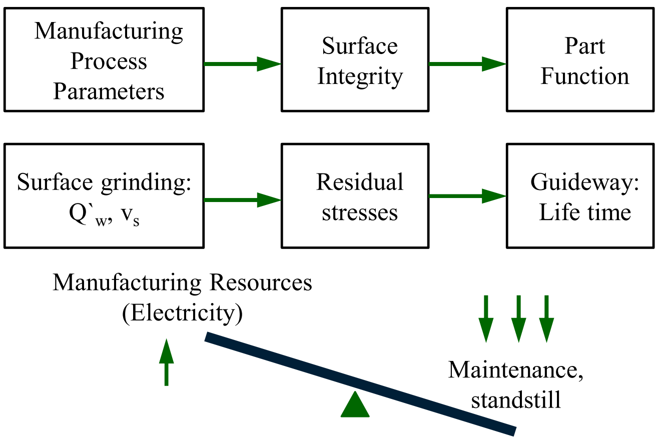


Figure 8. Influence of speed stroke grinding on product life, after [27, 29]

The parameters in the grinding process, here material removal rate, Q'_w, and grinding wheel speed, v_s, have an influence on the residual stresses in the product surface layer. In case of a guideway undergoing rolling contact load, the surface integrity has impact on the product life time. This would include maintenance cycles or standstill because of crack inspection or machine tool repair. A small increase in manufacturing effort, such as electricity and machining time, can result in much higher tradeoffs through reduced maintenance effort. This concept can be called leveraging [26].

Another example for leveraging precision manufacturing was obtained in a gear grinding process [27]. Higher efforts in producing higher surface quality result in higher mesh efficiency of a gear pair. As a consequence, the entire drive train of an automotive will consume significantly less energy in its whole use phase [27].

Today the product sustainability is still often considered only within the use phase of a product. Product design offers many opportunities to reduce the environmental impact of products. In many mechanical products the use phase dominates the energy consumed over the material extraction, manufacturing chain or transport. In this case, the strategy is to minimize mass (if the product is part of a system that moves), to increase thermal efficiency (if a thermal or thermo-mechanical system), or to reduce electrical losses (if an electro-mechanical system) [25]. However, the capabilities of manufacturing technology to improve eco-efficiency of products should not be underestimated besides product design [26].

In the last years, the increasing environmental consciousness has necessarily led to incorporating environmental impacts of manufacturing processes and process chains. However, the wider view encompasses how manufacturing processes can enhance the product life cycle.

CONCLUSION

A competitive and sustainable manufacturing technology should be based on energy awareness. Therefore, the above shown research considers the energetic aspects of speed-stroke grinding combined with high speed manufacturing. Both the theoretical and experimental results prove that the combination enhances process performance and workpiece quality.

Moreover, a leveraging effect of speed-stroke grinding with CBN wheels was discussed. After grinding less tensile residual stresses or even compressive residual stresses were obtained. These can prolong the product life for rolling contact or cyclic load applications by reducing crack initiation and crack propagation. Components with smaller wear result in enhanced overall environmental impact.

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