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Combination of Speed Stroke Grinding and High Speed Grinding with Regard to Sustainability

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Abstract

Production engineering is under constant pressure to satisfy demands for improved productivity while simultaneously achieving high workpiece quality. In addition, environmental awareness is a growing concern to address. New technologies represent new opportunities for increased productivity. This paper shows how the combination of speed stroke grinding and high speed machining can boost both process performance and workpiece quality. Theoretical consideration is validated by experiments and analyzed regarding energetic and environmental aspects. Only a thorough choice of process parameters leads to high process sustainability. Furthermore, lower tensile stresses can positively leverage increased manufacturing effort to optimize the overall product life cycle.

Keywords:

Grinding, High-speed machining, Energy awareness

1 INTRODUCTION

Production engineering is under constant pressure to satisfy industrial demands for improved productivity while also achieving high workpiece quality. Furthermore, growing environmental awareness is an additional requirement that production engineers must increasingly address. There are still several gaps in the evaluation of process eco-efficiency and material effectiveness [1]. Holistic data is hard to obtain and system boundary selection can strongly affect the assessment.

Establishing a sustainable manufacturing strategy requires metrics for decision making at all levels of the enterprise. To design these metrics, the company's goals (i.e. the concerns to address and the appropriate metric type to achieve the goals) and the scope (i.e. the appropriate geographic and manufacturing extent) have to be defined [2]. Suitable metric types include energy use, global climate change, non-renewable resource consumption, and water consumption.

Grinding has been historically regarded as only a finishing operation at the end of the process chain. But abrasive processes today also offer a large potential for high performance machining. The main kinematic process parameters table speed, v_w , depth of cut, a_e , and grinding wheel speed, v_s , have a high influence on the thermal and mechanical effects in surface grinding [3].

New technologies like speed stroke grinding represent new ways to increase productivity. This surface grinding method is pendulum grinding with increased table speeds. Advantages arise from the changing active chip formation mechanisms [4, 5, 6]. Disadvantages like high wheel wear may be resolved by combining speed stroke grinding with high speed machining and its intrinsic mechanisms to decrease chip sizes and forces [7, 8]. This paper shows promising results for enhanced process performance and workpiece quality by combining two grinding strategies.

2 MECHANISMS IN GRINDING PROCESSES

2.1 Basic considerations

The specific material removal rate, Q'_w , is often used to compare different grinding processes by productivity. The specific material removal rate can be increased by changing the table or workpiece speed, v_w , or the depth of cut, a_e (equation (1)).

$$Q'_w = a_e \cdot v_w \quad (1)$$

Thermal and mechanical effects are superimposed in grinding processes and strongly affect surface integrity. The influence of fundamental parameters can be explained based on the maximum undeformed chip thickness, $h_{cu,max}$ (equation (2)) [9-13].

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

where c_{gw} is the constant for grinding wheel topography, d_{eq} is the equivalent grinding wheel diameter, and e_1 is an exponent based on experimental regression analysis.

The grinding mechanisms can also be evaluated by the grinding energy, e_c , which is calculated using the specific tangential force, F'_t , the grinding wheel speed, v_s , and the specific material removal rate, Q'_w (equation (3)) [14].

$$e_c = \frac{F'_t \cdot v_s}{Q'_w} \quad (3)$$

The grinding energy, e_c , is the energy expended per unit volume of material removal, which is the sum of the energies of chip formation, e_{ch} , friction, e_{fr} , workpiece deformation, e_{def} , and the kinetic energy of the chips, e_{kin} .

2.2 Potential of speed stroke grinding

The speed stroke grinding process is a promising technology with table speeds up to 200 m/min and accelerations up to 50 m/s² [6, 15]. Inasaki performed the first study of speed stroke grinding on ceramics and

showed its capability [4]. Zeppenfeld investigated the technological principles of chip formation and wear mechanisms for increasing table speeds when grinding γ -titanium aluminides [6]. Nachmani focused on steel and described both the mechanical and thermal influence of speed stroke grinding [15]. Both authors showed the advantages of grinding with high table speeds. Essentially the mechanism of chip formation changes with increasing table speeds because the chip formation starts earlier and the maximum undeformed chip thickness grows [4, 6]. Therefore, the proportion of the elastic and plastic deformation diminishes in favor of earlier chip removal. Friction processes at the grit are reduced resulting in lower heat generation and a smaller grinding energy, e_c . In addition, the total number of active cutting edges increases with increasing table speed due to the lower chip thickness. In contrast, the momentary number of cutting edges, $\bar{N}_{\text{mom}}$, or the active number of cutting edges per unit time, decreases with increasing table speed (equation (4)) [6, 11, 12].

$$\bar{N}_{\text{mom}} \sim v_w^{-\frac{1}{3}} \quad (4)$$

The force load per single grit increases, which leads to possible grit breakouts and bond breakage. Besides these single grit effects, high table speed reduces the contact time of the heat dissipation into the surface layer.

The high table speeds and accelerations in speed stroke grinding require new machine concepts [6]. Conventional feed drives are based on bearing spindles. However, their vibration behavior, heat generation during use, and higher wear reduce the possible speed, acceleration, and accuracy of the process. Therefore, linear motors are used in actual machine concepts, which enable high table speeds and accelerations [6]. Nevertheless, high dynamical loads on the machine can result. An impulse isolation of the main drive and machine was implemented in the machine prototype used in this study [6]. A damping mass was attached to the machine bed via a spring damper system. An eddy current brake supported the passive damping.

2.3 Potential of high speed grinding

For high speed grinding (i.e. high grinding wheel circumferential velocities) different authors have shown the positive influence of the higher cutting speed on the surface integrity [7, 8, 16, 17, 18]. If all other parameters are constant, then increasing the grinding wheel speed results in a smaller chip thickness (equation (2)). Increasing the grinding wheel speed also reduces the grinding forces and improves surface quality in terms of average roughness height. Moreover, the radial grinding wheel wear decreases, which extends the life of the grinding wheel and improves resource efficiency.

However, higher wheel speeds result in higher grinding power, P_c , which is the product of the tangential grinding force, F_t , and the cutting speed, v_c (equation (5)). The cutting speed, v_c , equals the grinding wheel speed, v_s , with the difference of the workpiece speed, v_w , (equation (6)). For the calculation of v_c for most processes the workpiece speed, v_w , is negligible. The grinding power rises because the decreasing single grit forces do not compensate the increasing wheel speed. Higher grinding power results in higher temperatures. Therefore, the process strategy has to consider the thermal load and its influence on the surface integrity of the workpiece.

$$P_c = F_t \cdot v_c \quad (5)$$

$$v_c = v_s \pm v_w \quad (6)$$

Ferlemann investigated grinding wheel speeds up to 500 m/s with a galvanic bonded CBN grinding wheel and showed that an optimum operating point exists at $v_s = 220$ m/s in terms of low grinding forces and grinding power [7]. However, in practical application the grinding wheel speed varies between 60 to 200 m/s. Recently Oliveira, et al. studied actual trends for commonly used grinding wheel velocities in the grinding machine industry with a focus on CBN grinding wheels [19]. Most machine manufacturers focus on grinding wheel velocities of 40 to 80 m/s. Only 13 % of the 23 surveyed manufacturers mainly use 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 and high costs required. Furthermore, the grinding wheel layout has to be adapted to higher burst speeds.

The small utilization of high speed grinding is remarkable in consideration of the discussed and obvious advantages of reduced chip thicknesses. Regarding process sustainability, it can be expected that the enhanced process performance by high speed machining leads to higher resource and energy efficiency.

2.4 Expected mechanisms by process combination

We anticipate that the combination of speed stroke and high speed grinding leads to higher material removal rates without structural workpiece damage. The undeformed chip thickness from equation (2) remains constant if the table speed, v_w , and the grinding wheel speed, v_s , are increased proportionally with a constant grinding speed ratio, v_s/v_w . With this method the specific material removal rate, Q'_w , can be increased without a change in the chip thickness, grinding force, or surface quality.

This correlation is implemented in Badger's "Aggressiveness Number," which is an adaption of equation (2) that is easier to calculate for machine users [20]. However, the working range for a given wheel and workpiece combination has to be initially found.

To hold the specific material removal rate constant in different process strategies, the depth of cut and workpiece speed have to be adapted (equation (1)). Because both parameters have different influences on the maximum undeformed chip thickness, different process mechanisms can be adjusted. The table speed has a stronger influence on the maximum undeformed chip thickness than the depth of cut (equation (2)).

3 PRACTICAL VALIDATION

3.1 Test set-up

The hypothesis of enhancing speed stroke grinding with high speed machining was validated with experimental investigations on the speed stroke grinding machine Blohm Profimat MT 408 HTS. This machine tool is also in the focus of coupling a process model and a machine tool model to predict the process stability [21]. AISI 52100 hardened steel was machined using vitrified bonded CBN grinding wheels (B181 LHV 160, $d_g = 400$ mm, Tyrolit) for the experiments that increased table speeds and grinding wheel velocities.

CBN grinding tools have higher wear resistance than conventional tools of corundum, which results in reduced waste. Due to the higher thermal conductivity, positive compressive stresses can often be added to the workpiece surface. Nevertheless, these tools are much more expensive than conventional tools and need high

wheel velocities and subsequently high spindle power to achieve their advantages. Therefore, the proper process window is crucial for sustainable usage of CBN abrasive tools.

Tool conditioning was performed with a diamond form roller. The parameters were chosen to achieve a relatively high effective grinding wheel surface roughness (overlap ratio of $U_d = 4$, depth of dressing cut of $a_{ed} = 3 \mu\text{m}$, wheel speed in dressing v_{sd} same as grinding wheel speed v_s , and speed ratio of $q_d = 0.8$, though the speed ratio for $v_s = 160 \text{ m/s}$ had to be lowered to $q_d = 0.6$ because the form roller speed was limited). All grinding and dressing operations used an emulsion of 5 % oil in water (Ecocool 2525 HP, Fuchs) as a cooling lubricant.

A Kistler 3-component dynamometer with a piezoelectric force transducer was used to measure grinding forces. The relevant process parameters were systematically varied during the grinding tests with a maximum specific material removal of $V'_w = 1000 \text{ mm}^3/\text{mm}$. The table speed was increased from $v_w = 12 \text{ m/min}$ to 180 m/min and the grinding wheel speed was varied from $v_s = 80 \text{ m/s}$ up to 160 m/s . The specific material removal rate was held constant at the relatively high value of $Q'_w = 40 \text{ mm}^3/\text{mms}$ so that increasing table speeds were accompanied by decreasing depth of cut (equation (1)).

3.2 Process efficiency

The efficiency of a machining process can be evaluated by the energy expended per material removal. Here, the grinding energy was derived from the measured grinding forces according to equation (3). This is illustrated in Figure 1 for different table and grinding wheel speeds. As previously derived and shown in earlier work, the grinding energy decreased with increasing table speeds due to the more effective chip formation process at higher chip thickness. Higher circumferential wheel speeds increase the grinding energy because of the higher grinding power (equations (3) and (4)). However, this trend was minimized for higher table speeds (see Figure 1).

Figure 2 expands the efficiency analysis from the chip formation scale to the machine scale and estimates the grinding power, P_c , according to equation (5). The process time, t_{Process} , is a function of the table acceleration time, t_{acc} , workpiece length, l_w , and overrun length, l_g , as shown in equation (7). If more than one stroke is done to machine the total allowance, $a_{e \text{ total}}$, the acceleration time has to be considered a second time to decelerate the table at the turning point. The number of strokes is the allowance, $a_{e \text{ total}}$, divided by the depth of cut, a_e .

$$\text{For one stroke } t_{\text{Process}} = t_{\text{acc}} + \left(\frac{l_w + l_g}{v_w} \right) \quad (7)$$

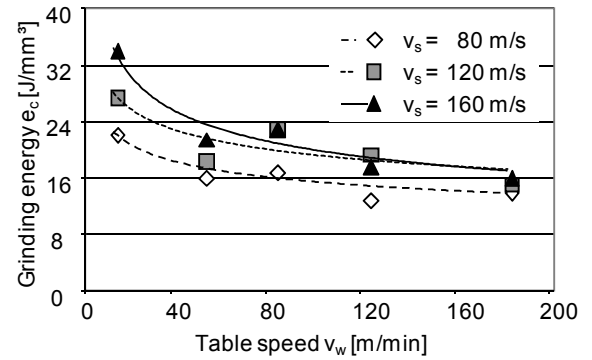
$$\text{For } > 1 \text{ stroke } t_{\text{Process}} = \frac{a_{e \text{ total}}}{a_e} \cdot \left(2 \cdot t_{\text{acc}} + \left(\frac{l_w + l_g}{v_w} \right) \right)$$

The table acceleration time, t_{acc} , is simplified by equation (8) for a uniform linear acceleration. The maximum machine acceleration of $a_w = 50 \text{ m/s}^2$ was used in the given considerations.

$$t_{\text{acc}} = \frac{v_w}{a_w} \quad (8)$$

The overrun length, l_g , is the same as the contact length and can be defined by equation (9) as the square root of the product of the depth of cut, a_e , and the grinding wheel diameter, d_g .

$$l_g = \sqrt{a_e \cdot d_g} \quad (9)$$

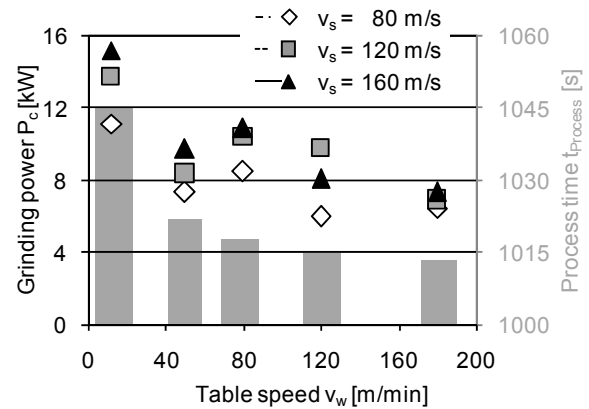


Grinding wheel	Parameter	Dressing
B181 LHV 160	$Q'_w = 40 \text{ mm}^3/\text{mms}$	$U_d = 4$
Material	$V'_w = 1000 \text{ mm}^3/\text{mm}$	$q_d = 0.6 - 0.8$
100Cr6	Coolant	$a_{ed} = 3 \mu\text{m}$
(AISI 52100)	Emulsion (5%)	

Figure 1: Specific energy as a function of table speed and grinding wheel speed.

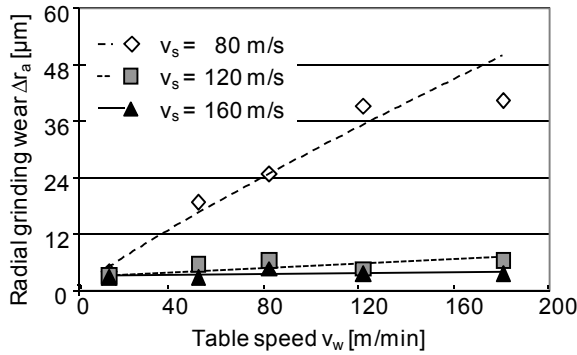
The grinding power (see Figure 2) had a trend similar to the specific grinding energy (see Figure 1). Specifically, both values depended on the measured tangential forces with a constant material removal rate. However, as the grinding power equals the spindle power, higher table speeds reduced the consumed power significantly. Moreover, at $v_w = 180 \text{ m/min}$ all wheel speeds had nearly the same spindle power.

The process time has to be known to estimate the power consumption or energy usage during the grinding process. Reducing the process time decreases the consumed resources in the process as whole. In Figure 2 the process time was estimated with equation (7) for a workpiece length of $l_w = 200 \text{ mm}$. Despite the growing acceleration times, the process time decreased by around 3 % from $v_w = 12$ to 180 m/min , which would additionally lessen the power consumption.



Grinding wheel	Parameter	Dressing
B181 LHV 160	$Q'_w = 40 \text{ mm}^3/\text{mms}$	$U_d = 4$
Material	$V'_w = 1000 \text{ mm}^3/\text{mm}$	$q_d = 0.6 - 0.8$
100Cr6	Coolant	$a_{ed} = 3 \mu\text{m}$
(AISI 52100)	Emulsion (5%)	
Assumptions for process time calculations		
$l_w = 200 \text{ mm}$ $a_{e \text{ total}} = 0.2 \text{ mm}$		

Figure 2: Grinding power and process time as a function of table speed and grinding wheel speed for a workpiece length of $l_w = 200 \text{ mm}$.



Grinding wheel	Parameter	Dressing
B181 LHV 160	$Q'_w = 40 \text{ mm}^3/\text{mms}$	$U_d = 4$
Material	$V'_w = 1000 \text{ mm}^3/\text{mm}$	$q_d = 0.6 - 0.8$
100Cr6	Coolant	$a_{ed} = 3 \text{ } \mu\text{m}$
(AISI 52100)	Emulsion (5%)	

Figure 3: Radial grinding wear as a function of table speed and grinding wheel speed.

The assumed workpiece length is even quite small considering linear guideways as typical application for surface grinding. The process times will converge for longer workpieces, which emphasizes the need for reduced grinding power.

The theoretical considerations have to be carefully included because the processing power can be a minor part in the total power demand of machine tools depending on the degree of automation or presence of energy sinks especially in the machine periphery [22]. This emphasizes even more the need to reduce process time. The power consumed by the total machine including table axes and periphery was not measured in this study, but should be in future work.

The radial grinding wheel wear is another important value for process efficiency because the tool life affects product costs and auxiliary times such as dressing or tool change. The radial grinding wheel wear increased with higher table speeds in this study (see Figure 3), which is due to thicker chips and higher single grit loads. However, the wear declined rapidly with rising grinding wheel speed. This can be explained by smaller undeformed chip thickness and lower single grit forces.

The thermal impact on tool and workpiece increased with higher grinding wheel speed. With higher table speeds, though, fewer grits are engaged within the grinding zone for the same period of time, which results in a reduced amount of time for the thermal heat to flow (see Figure 5). Both the smaller chip thickness and reduced heat induced lower wheel wear.

Although the wheel speeds of $v_s = 120 \text{ m/s}$ and 160 m/s did not show much of a difference in these results, the higher cutting speed allows for raising the material removal rate above $40 \text{ mm}^3/\text{mms}$.

3.3 Workpiece quality

As discussed previously, the workpiece surface roughness followed a trend similar to the undeformed chip thickness – i.e. increasing roughness with higher table speeds or lower wheel speeds. Not surprisingly the average roughness height, R_a , increased in these experiments for higher table speeds. But, simultaneously increasing the grinding wheel speed minimized this trend (see Figure 4). From $v_s = 80$ to 160 m/s the undeformed chip thickness is halved in theory.

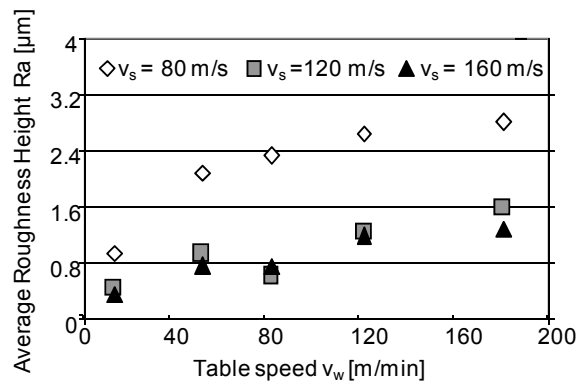
The combined thermo-mechanical load applied during grinding can influence the residual stresses in the surface layer, which causes changes in the structure and

hardness of the workpiece and leads to cracks and undesired textures [3]. However, no structural damage occurred for all experiments in the speed stroke grinding regime. Increased table speeds reduced the contact time between the tool and workpiece [23]. It also minimized the total heat transferred into the surface layer due to the more effective chip formation.

Figure 5 shows temperature measurements and simulation results for the most critical wheel speed of $v_s = 160 \text{ m/s}$. The experimental data was obtained by a two-color pyrometer that had a high time resolution of $2 \text{ } \mu\text{s}$. For a table speed of 12 m/min , the highest temperature was measured to be about $600 \text{ }^\circ\text{C}$. In the speed stroke grinding regime of $v_w \geq 50 \text{ m/min}$, the temperatures were below $320 \text{ }^\circ\text{C}$, which clearly shows the advantages of increasing chip thickness on temperature. Recent research has developed a FEA model to simulate the temperature occurring in speed stroke grinding [23, 24]. The model predicts the descent of the maximum temperature and has deviations of less than $80 \text{ }^\circ\text{C}$ between experimental and simulated maximum temperatures for table speeds up to $v_w = 80 \text{ m/min}$ (see Figure 5). However, implementing deformation energy and grinding mechanisms can enhance the model. As a consequence of lower process temperatures, the amount of cooling lubricant could also be reduced, which would reduce both waste and auxiliary energy.

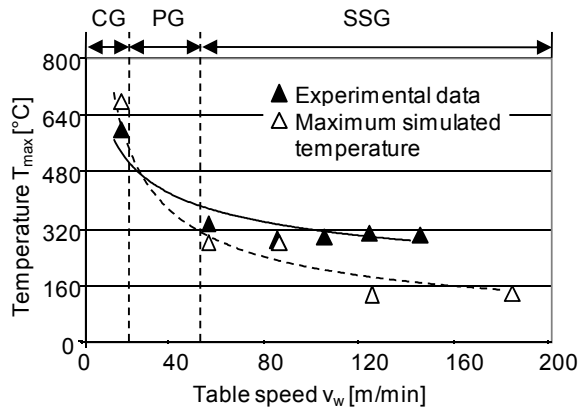
In the experiments the surface layer was machined unharmed by thermal impact [23]. Figure 6 illustrates the residual stresses for all three table speeds $v_w = 12 \text{ m/min}$, 80 m/min , and 180 m/min for the maximum wheel speed $v_s = 160 \text{ m/s}$. At a table speed of $v_w = 12 \text{ m/min}$, tensile residual stresses above 500 MPa occurred with an annealed zone. However, less heat converted into the surface layer, the mechanical impact grew dominant, and a compressive residual stress was induced at higher speeds [23]. Additionally, the high thermal conductivity of the abrasive material CBN supported the lower thermal impact on the workpiece.

Compressive stress enhances the product life for most applications, which is an important factor in overall sustainability considerations. For example, the rolling contact fatigue life is affected by residual stresses by both changing the crack initiation life and the crack propagation life [25]. In addition, adding a compressive stress through grinding can shorten the process chain by substituting subsequent procedures [26].



Grinding wheel	Parameter	Dressing
B181 LHV 160	$Q'_w = 40 \text{ mm}^3/\text{mms}$	$U_d = 4$
Material	$V'_w = 1000 \text{ mm}^3/\text{mm}$	$q_d = 0.6 - 0.8$
100Cr6	Coolant	$a_{ed} = 3 \text{ } \mu\text{m}$
(AISI 52100)	Emulsion (5%)	

Figure 4: Surface roughness as a function of table speed and grinding wheel speed.



Grinding wheel	Parameter	
B181 LHV 160	$Q'_w = 40 \text{ mm}^3/\text{mms}$	$v_s = 160 \text{ m/s}$
Material	$V'_w = 1000 \text{ mm}^3/\text{mm}$	
100Cr6	Coolant	
(AISI 52100)	Emulsion (5%)	

Figure 5: Measured and simulated temperature as a function of table speed for $v_s = 160 \text{ m/s}$ (CG: conventional grinding, PG: pendulum grinding, SSG: speed stroke grinding) [24].

4 CONCLUSIONS

Theoretical considerations for increasing table and wheel speeds indicated that a combined growth of both parameters could suppress the individual challenges in grinding. FEA models for temperature and residual stress prediction promise to reduce experiments and approach first-time right production in the future [23, 24]. Moreover, modeling is a sufficient means to increase process stability for higher resource and energy efficiency [1]. The theoretical considerations of speed stroke grinding represent a first step towards characterizing process mechanisms and improving resource efficiency.

The experimental results proved that the combination of speed stroke grinding and high speed machining can decrease grinding energy, grinding power, and tool wear. The increase in workpiece surface roughness caused by higher table speeds was acceptable in the scope of roughing operations. Moreover, the worsening of surface roughness could be slowed down through simultaneously applying higher grinding wheel speeds.

For shorter production times, suitable product quality was generated while simultaneously requiring less cooling lubricant. Additionally, the grinding wheel spindle power was reduced. However, energy considerations for the total machine power were not included because we did not consider the used prototype machine as presentable regarding overall machine energy consumption. New machine concepts using energy-adjusted machine components have been developed to address these issues.

The combination of speed stroke grinding and high speed machining represents a new technology capable of high performance machining. This process, though, still has potential for improvement. For example, the improvement of product life is possible by adding compressive stresses. Enhancing the product life cycle in this way is a means of leveraging improvements to grinding technology to drive decreased product life cycle impacts.

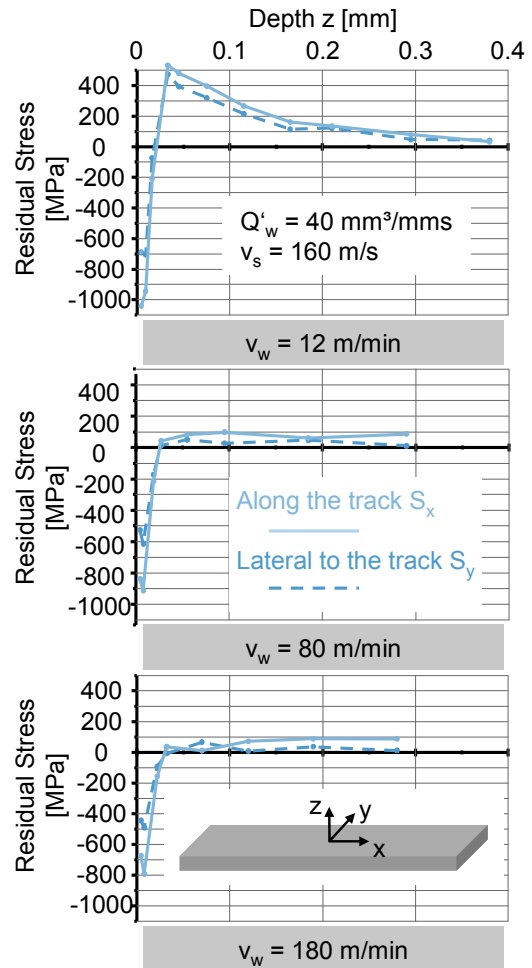


Figure 6: Residual stress as a function of table speed [23].

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