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INVESTIGATION OF TEMPERATURES AND RESIDUAL STRESSES IN SPEED STROKE GRINDING VIA FEA SIMULATION AND PRACTICAL TESTS

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Abstract: *The new technology of speed stroke grinding promises to meet the industrial demand for a high-efficiency, high-quality finishing process. The surface layer properties of the workpiece, such as residual stresses, are a vital factor in the quality of the workpiece and must be considered when choosing process parameters. This paper discusses the residual stresses resulting from practical speed stroke grinding tests of hardened steels using CBN grinding wheels, as well as an in-development FEA model for the thermal aspects of speed stroke grinding.*

Key words: *speed stroke grinding, residual stress, FEA-simulation.*

1. INTRODUCTION

Industrial demand for high efficiency grinding operations leads to the development of new processes to improve performance. These new technologies must also fulfil existing requirements regarding surface properties such as residual stresses in the surface layer.

The combined thermo-mechanical loading applied to the workpiece during grinding can influence the residual stresses in the surface layer, cause changes in the structure and hardness of the workpiece and lead to cracks and undesired textures [1]. For steel workpieces, potential thermal effects may include surface oxidation (often merely superficial), thermal softening (tempering), residual tensile stresses or re-hardening due to formation of martensite [2]. High tensile residual stresses in particular can promote the formation of cracks in the material, while compressive residual stresses tend to hinder crack formation and improve fatigue life [2]. This leads to specific demands on new grinding technologies: compressive residual stresses on the workpiece surface are desired, while thermal damage must be avoided.

Speed stroke grinding is a promising new technology that uses high table speeds up to v_w = 200 m/min and accelerations up to a_w = 50 m/s^2 to provide high removal rates and increased product quality [3, 4]. Zeppenfeld investigated the technological principles of chip formation and wear mechanisms for speed-stroke grinding of γ-titanium aluminide using a diamond grinding wheel with vitrified bond [4]. However, his results and insights cannot be transferred directly to the grinding of hardened steels due to the specific properties of the γ-titanium aluminide workpiece material. Nachmani was the first to investigate speed stroke grinding of hardened steels through his experiments with conventional grinding wheels [5]. It was shown that the adoption of speed stroke grinding can simultaneously improve both the compressive residual stress of the workpiece surface layer and the material removal efficiency. The effects of CBN grinding wheels in speed stroke grinding of hardened steels has not yet been considered, and will be discussed in this paper.

To fully and effectively use this new technology, appropriate ranges of process parameters must be found that avoid workpiece damage or even produce desirable effects on the workpiece (such as compressive residual stress at the surface). Empirical determination of these process parameters is time-consuming, expensive, and provides little insight into the fundamental physical processes taking place. Process modelling and simulation, on the other hand, have proven to be efficient and valuable tools for estimating the effects of mechanical and thermal loads on the workpiece, which allows for better planning of grinding processes [6, 7, 8].

The latest review by Doman et al. [9] gives a comprehensive overview of FEA grinding models between 1995 and 2009. Although a number of researchers have used FEA models to investigate grinding, models of speed stroke grinding are lacking.

The current work analyses the mechanical and thermal loads on the workpiece surface using experimental speed stroke grinding tests with hardened steel workpieces (100Cr6, AISI 52100, HRC 62) and CBN grinding wheels. Based on these practical tests, the speed stroke grinding process is modelled for the first time using FEA in order to investigate the thermal grinding loads. These results are compared to metallurgical specimens from the test workpieces. Furthermore, initial conclusions are drawn about the residual stresses in the ground workpieces due to different table speeds.

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2. THEORETICAL AND EXPERIMENTAL INVESTIGATION OF SPEED STROKE GRINDING

2.1. Theoretical consideration of mechanical and thermal influences in speed stroke grinding

Chip formation during grinding can be divided into three phases. The initial contact between the abrasive grain and the workpiece causes only elastic deformation and subsequently leads to plastic deformation before actual chip formation begins. Chip formation occurs in the direction of the largest sheer stress [10].

The amount of energy needed to remove a specific material dimension during the grinding process can be described with the specific grinding energy e_c [16].

$$e_c = \frac{F_t \cdot v_c}{Q_w} = \frac{F'_t \cdot v_c}{Q'_w} . \tag{1}$$

In Eq. 1, F_t is the tangential force, Q_w is the material removal rate, v_c the grinding wheel velocity, F'_t is the specific tangential force and Q'_w is the specific material removal rate. The specific grinding energy e_c can be divided into the following components: the energy of chip formation e_{ch}, of friction e_{fr}, of workpiece deformation e_{def} and of kinetic energy of the chips e_{kin}, as seen in Eq. 2.

$$e_c = e_{ch} + e_{def} + e_{fr} + e_{kin} . \tag{2}$$

The kinetic energy e_{kin} of the chips is a negligible portion of the total energy e_c [4]; furthermore, the specific chip formation energy e_{ch} is heavily dependent on chip formation and decreases with increasing chip thickness due to the chip formation threshold depth T_μ being reached at an earlier stage [4]. The dominant mechanical energy component during chip formation is the specific deformation energy e_{def}, which consists of the energy proportion used to elastically and plastically deform the workpiece material. The specific friction energy e_{fr} is almost completely transformed into heat and is thus reflected in the thermal effects [17].

The thermal impact can be described in more detail by the energy-related process parameters such as the area specific grinding power P''_c and the area specific grinding energy E''_c. The area specific grinding power is given by Eq. 3, which is assumed to be equal to the heat q_t generated in the process [19–22].

$$P''_c = q_t = \frac{F'_t \cdot v_c}{l_g} . \tag{3}$$

The contact length is calculated by Eq. 4 from the depth of cut a_e and the grinding wheel diameter d_s.

$$l_g = \sqrt{a_e \cdot d_s} . \tag{4}$$

Because the table speed v_w is increased in speed stroke grinding while the specific material removal rate Q'_w is held constant, the depth of cut a_e and therefore the contact length l_g is significantly reduced [18].

Since the geometric contact length, given by Eq. 4, decreases with increasing table speeds at a constant specific material removal rate, pendulum (PG) and speed stroke grinding (SSG) processes feature smaller contact areas between the grinding wheel and workpiece than those which occur in creep feed grinding (CG). The grinding forces, however, decrease significantly more slowly than the contact area. This results in an elevated area specific grinding power P''_c.

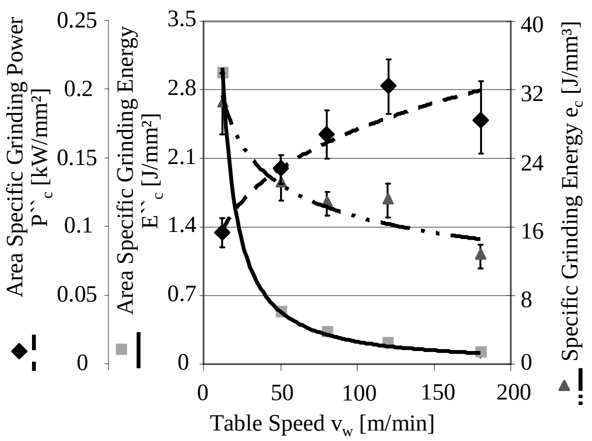
In contrast, the area specific grinding energy will decrease with increasing table speeds due to reduced contact time. E''_c describes the energy input per unit square into the workpiece. Hence, the thermal impact on the surface layer can be estimated using Eq. 5.

$$E''_c = \frac{F'_t \cdot v_c}{v_w} . \tag{5}$$

2.2. Experimental Validation

Grinding tests were conducted on a speed stroke grinding machine Blohm Profimat MT 408HTS with a vitrified CBN grinding wheel (B 181). In order to measure grinding forces, a 3-Component-Dynamometer including a piezo-electric force transducer from Kistler was used. Apart from this, the residual stress in the workpiece material 100Cr6 (AISI 52100, HRC 62) was analysed by X-ray diffraction. The lattice strain measurements are done at the {211} lattice plane of the martensitic phase with Cr-Ka radiation. The stresses are calculated from this using the Dölle-Hauk method and the X-ray elastic constants $½s_2 = 5.76 \cdot 10^{-6}$ MPa^{-1} and $s_1 = -1.25 \cdot 10^{-6}$ MPa^{-1}. During the grinding tests, the process parameters were systematically varied with a maximum specific material removal of V'_w = 1000 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 = 100 m/s up to 160 m/s.

In Fig. 1, the area specific grinding power P''_c, the area specific grinding energy E''_c and the specific grind-



Grinding wheel	Parameter	Coolant
B181 LHV 160	v_w = 12 -180 mm/min	Emulsion (5 %)
Material	v_s = 100 - 160 m/s	**Dressing parameter**
100Cr6 (HRC 62)	Q'_w = 10 - 40 mm³/mms	U_d = 4
	V'_w = 1000 mm³/mm	q_d = 0.6 – 0.8
		a_{ed} = 3 µm

Fig. 1. Variation of grinding energy and power for different table speeds.

ing energy e_c are illustrated for different table speeds v_w. Although the area specific grinding power P_c'' increased with higher table speeds, the area grinding energy E_c'' and specific grinding energy e_c decreased. This fits well to the theoretical consideration from above. Consequently, it can be assumed that the thermal influence was decreased. The following FEA simulation was conducted to demonstrate the change of thermal impact for the different surface grinding strategies.

3. FEA SIMULATION FOR SPEED STROKE GRINDING

3.1. Development of FEA Model

An extensive literature review has been carried out to find an appropriate approach to model the speed stroke grinding process. In particular, the structural changes as well as the residual stress should be implemented.

In 1995, Mahdi and Zhang [11] presented a 2D thermal model for the grinding of alloy steel, which they used to predict the formation of martensite. Their temperature model showed good agreement with existing analytical models. Later on, Mahdi and Zhang developed a thermo-structural model [12] that considers formation of martensite, thermally-induced stresses and work hardening. Neither of these models was experimentally validated. Doman et al. [9] consider Mahdi and Zhang's thermo-structural grinding model to be the most comprehensive available. Moulik et al. [13] and Hamdi et al. [14] developed similar model setups to study thermally-induced residual stresses in surface grinding at low table speeds. Moulik et al. included both a mechanical load and a thermal load in modelling the grinding wheel effects, while Hamdi et al. used only a thermal load. Both found predominantly tensile stresses near the surface of the workpiece, although Hamdi et al. hypothesized that martensite formation would occur in cases with higher grinding temperatures, leading to compressive residual stress. Neither study included experimental validation. Anderson et al. [15] developed 2D and 3D thermal models, both with and without modelling the material removal at the surface, and checked them against experiments. They attempted to determine which types of models (i.e. analytical, 2D FEA, 3D FEA, with material removal and without material removal) were suitable for modelling different grinding processes. The models presented by Doman et al. deal almost exclusively with surface grinding at low table speeds or with external cylindrical grinding. The different cutting mechanisms that arise during speed stroke grinding were not considered. In our research, the temperature distribution is modelled in order to obtain a better understanding of thermally induced residual stresses. In the future, this model will be combined with a mechanical load model and material science will be specially regarded for structural changes.

3.2. FEA Temperature Model Realisation

In a surface grinding process, the workpiece is fed past the grinding wheel at the table feed speed, v_w. Material deformation and friction produce heat in the contact

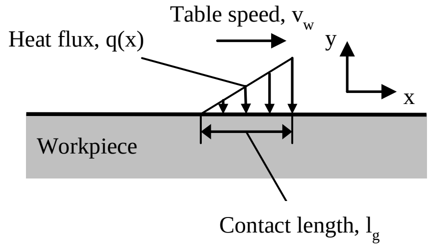


Fig. 2. Model schematic.

zone between the wheel and the workpiece, where the heat dissipates into the grinding wheel, the coolant, the chips, and the workpiece.

This system can be thermally modelled as a heat source moving over a stationary workpiece at the table speed v_w, as shown in Fig. 2. The current model in the FEM-software Abaqus assumes a two-dimensional, plane strain problem with temperature-independent material properties. The heat produced in the process is represented by a right triangular heat flux profile, as shown in Fig. 2. Studies have shown that models with a triangular heat flux give better accuracy than those with a uniform heat flux [6, 14, 19, 18–27]. The heat flux is applied over the geometric contact length l_g, which is calculated according to Eq. 4.

The workpiece surface is considered to be flat, and the material removal at the workpiece surface is neglected; Anderson et al. [15] found that for small depths of cut, such as those considered in this work, simulations without material removal were more accurate than simulations with material removal.

The heat flux $q(x)$ (shown in Fig. 2) applied to the top surface of the workpiece at any time t is modelled by Eq. 6, where q_w is the average heat flux magnitude of the heat source and $x_{lg,\min}(t)$ and $x_{lg,\max}(t)$ are the lower and upper boundaries of the contact zone. The contact zone boundaries $x_{lg,\min}(t)$ and $x_{lg,\max}(t)$ vary with time in order to move the heat source along the workpiece in the positive x-direction. The boundaries for other workpiece surfaces are considered as semi-infinite.

$$\mathrm{q(x)} = \begin{cases} \dfrac{2 \cdot q_w}{l_g}(x - x_{lg,min}(t)) & \text{for } x_{lg,min}(t) \le x \le x_{lg,max}(t) \\ 0 & \text{for } x < x_{lg,min}(\mathrm{t}) \text{ and } x > x_{lg,max}(t) \end{cases} . \quad (6)$$

To determine the magnitude of the heat source, it is assumed that the grinding power is completely converted into heat [17], which allows the total heat q_t produced in the grinding zone to be calculated based on the tangential force F_t measured in grinding experiments, as previously shown in Eq. 3. Figure 1 shows the grinding power associated with each table speed. The total heat flux q_t divides into heat flows into the grinding wheel (q_s), the chips (q_{ch}), the coolant (q_{cool}) and the workpiece (q_w), as shown in Eq. 7 [28].

$$q_t = q_s + q_{ch} + q_{cool} + q_w \,. \quad (7)$$

Rearranging Eq. 7 and introducing the factor R_{ws}, which describes the heat allocation between the grinding wheel and the workpiece, yields Eq. 8 for the average heat source magnitude, q_w [29, 30].

$$q_w = (q_t - q_{ch} - q_{cool}) \cdot R_{ws} \, . \tag{8}$$

The heat transfer coefficient of the coolant in the grinding zone is estimated using the equation for forced convection over a flat plate, assuming a fluid velocity equal to the grinding wheel velocity, v_s [18]. The boiling temperature of the coolant must also be considered, since the boiling temperature is the maximum temperature the fluid will reach. In the current model, the change in cooling mechanism associated with boiling of the coolant is not considered; instead, the temperature of the coolant is simply limited to being less than or equal to the boiling temperature [31].

To define the maximum energy that can be absorbed by the chips, Malkin proposes a limit similar to the boiling temperature for the coolant. The energy absorbed by the chips is limited by the melting temperature of the workpiece material. For ferrous metals, the maximum specific grinding energy removed by the chips is approximately 6 J/mm^3 [32-33].

The workpiece material is 100Cr6 (AISI 52100), which was modelled using the properties shown in Table 1. The properties of the CBN grinding wheel are given in Table 2 and were used to determine the heat allocation between the workpiece and the grinding wheel. The average abrasive edge radius r_0 and the ratio of the wetted contact area A_{cool} to the total contact area A_c are assumed values based on previous research at the Laboratory of Machine Tools and Production Engineering (WZL) at the RWTH Aachen University.

3.3. Simulation Results

Determining the magnitude of the heat flow dissipated into the workpiece is critical for an accurate calculation of the workpiece temperatures. The fraction of the total grinding heat which enters the workpiece is the most important impact on the resulting surface layer quality. Different researchers have used values ranging from 5 and 85 % of the total grinding heat, depending on the grinding conditions [18, 21]. This clearly shows what large influence different process parameters can have on the partition of the grinding heat.

The heat partition was also used to compare the current model with previous work. Over the range of table speeds considered and over the entire temperature range for each speed, the heat partition in the current model varies between 19 and 32 %, which is consistent with the heat partitions found by Malkin [18] for CBN grinding wheels.

Table 1

Workpiece material properties

Workpiece material	**100Cr6 (AISI 52100)**	
Therm. conductivity, λ_w	39.6	W/(m·K)
Density, ρ_w	7810	kg/m^3
Specific heat capacity, $c_{p,w}$	461	J/(kg·K)
Melting temperature, T_m	1500	°C

Table 2

Grinding wheel properties

Grinding wheel	**vitrified bonded CBN**	
Therm. conductivity of abrasive, λ_s	1300 [37]	W/(m·K)
Average abrasive edge radius, r_0	0.000025	m
Fraction of contact area occupied by coolant, A_{cool} / A_c	0.9	

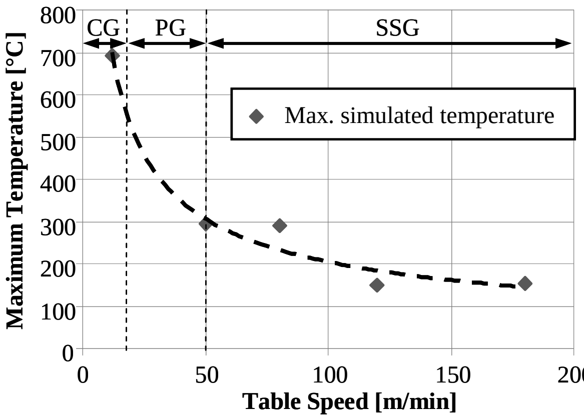


Fig. 3. Maximum predicted temperature for different table speeds.

The grinding temperatures were simulated for a constant material removal rate of $Q'_w = 40$ mm³/mms and grinding wheel velocity of $v_s = 160$ m/s at different table speeds with the results shown in Fig. 3. These parameters are expected to present the highest possibility of risk for thermal damage in the range of the experimental set-up.

For a table speed of $v_w = 12$ m/min, a maximum temperature of almost 700 °C is reached, which approaches the austenitisation temperature for hardened steels (Fig. 3), [40]. Temperatures close to the austenitisation temperature can lead to thermal damage (specifically softening or tempering of the steel) given sufficient time for carbon diffusion [24]. In contrast, all of the simulations for higher table speeds yielded maximum temperatures below 320 °C. Hence, no thermal damage is expected. A comparison of Fig. 1 and Fig. 3 shows that the area specific grinding energy and the maximum simulated temperatures both show a similar tendency to decrease with increasing table speed.

4. VALIDATION OF TEMPERATURE MODELLING

4.1. Comparison Between Experimental And Simulated Results

The functionality of the finished product is strongly affected by the condition of the surface layer, including the material structure and the residual stresses. This section will consider the structure and residual stresses resulting from the grinding tests and compare these results to the simulated temperatures.

Figure 4 shows the cross section of the experimental workpiece for a table speed of $v_w = 12$ m/min, which reached the highest simulated temperatures and was at the greatest risk for thermal damage. However, no tests, including the table speed of $v_w = 12$ m/min, produced thermal damage. This is consistent with the simulated maximum temperatures. In comparison to Nachmani's speed stroke grinding tests of hardened steels with conventional grinding wheels, the use of CBN shows high potential for avoiding structural damage [5]. This is explained by the higher thermal conductivity λ_s of CBN

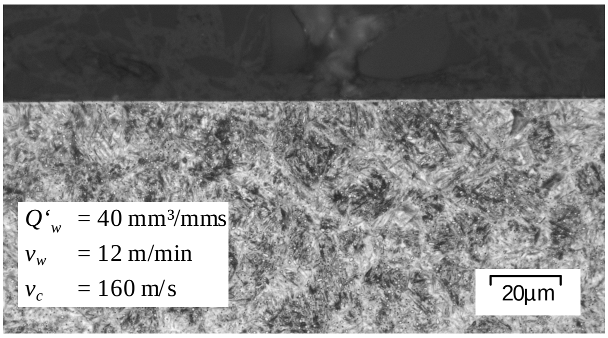


Fig. 4. Metallurgical specimen.

as well as the smaller average abrasive edge radius r_0.

In Fig. 5, the residual stress for table speeds of v_w = 12, 80 and 180 m/min are plotted versus the depth below the surface. Only the table speed of v_w = 12 m/min induced tensile residual stresses, which are assumed to be thermally induced. However, no thermal damage could be identified in any of the metallurgical specimens. So far, in all experiments the simulated temperatures were consistent with the specimens. The higher table speeds up to v_w = 180 m/min showed only compressive residual stresses. Hence, it is supposed that the mechanical load became dominant as the thermal load decreased.

Additionally, the kinematic contact length was reduced for higher table speeds going along with a smaller number of momentary cutting edges $\overline{N}_{mom}$ [4]. Simultaneously, the grinding normal force decreased with a smaller slope. This resulted in higher contact pressure in the grain-workpiece engagement which emphasised that the mechanical load became dominant.

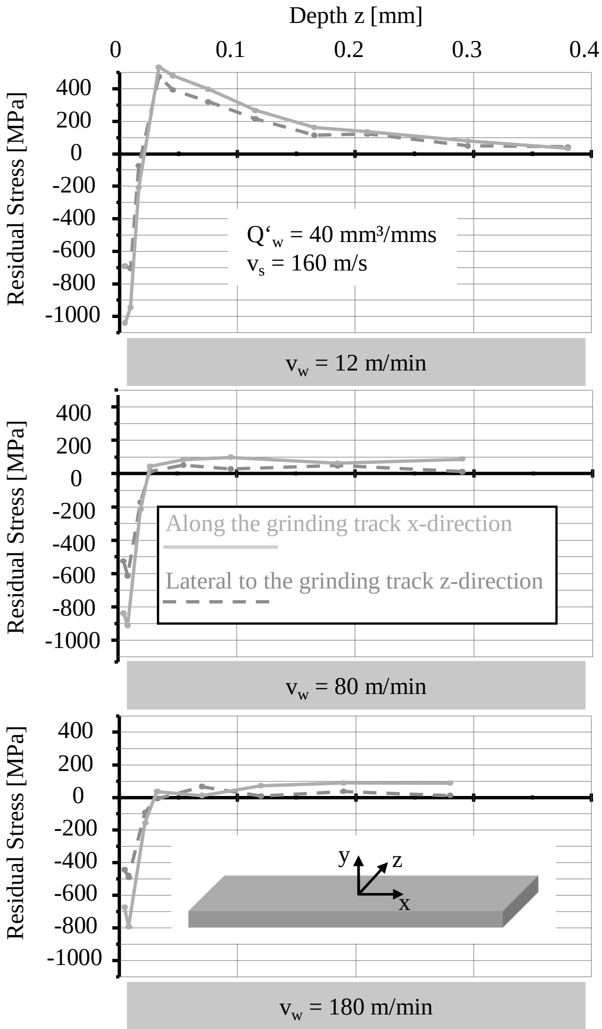


Fig. 5. Measured residual stress for speed stroke grinding.

4.2. Further Research

The FEA simulation shows promise for determining the temperatures in the workpiece during grinding. Further experiments including temperature measurement during the grinding process are planned to further verify the temperature FE-Model. Using the simulated temperature field, the thermally-induced residual stresses will be calculated and compared to experimental values. A mechanical FE-Model of speed stroke grinding is also under development to facilitate a better understanding of the individual influences of mechanical and thermal load on the final residual stresses.

Both the temperature simulation and the metallurgical specimen confirmed that no structural changes took place under the current grinding parameters. As the first residual stress model for speed stroke grinding will not able to consider structural changes, the identified grinding parameters are appropriate for the first verification. In future the model will be expanded with today lesser-understood aspects, such as structural change.

5. CONCLUSIONS

The theoretical considerations of thermal investigation were verified through grinding tests. Moreover, this paper documents the performance enhancement by the new technology of speed stroke grinding. The significant increase of table speeds and the introduction of CBN grinding wheel in speed stroke grinding of hardened steels yield a more reliable application for industry in terms of enhanced surface functionality.

In this paper, a FEA-model to simulate the temperature occurring in speed stroke grinding was developed. Hence, the thermal influence on the surface layer could be derived, which shows a strong correlation between the simulated temperature and the area specific grinding energy. The metallurgical structure and residual stresses were also experimentally determined and were consistent with the simulated temperatures.

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