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Experimental and Numerical Analysis of the Surface Integrity resulting from Outer-Diameter Grind-Hardening

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Abstract

Besides conventional heat treatment operations, an innovative approach for surface hardening is the grind-hardening process. During this process the dissipated heat from grinding is used for a martensitic phase transformation in the subsurface region of machined components. Additionally, compressive residual stresses are induced in the grind-hardened surface layer. However, for the implementation of grind-hardening into industrial production extensive experimental tests are required to achieve iterative results of hardening depth. This paper focuses on the identification of parameter sets for a sufficient grind-hardening in outer-diameter grinding. On the one hand, grinding tests were conducted supported by metallographic investigations; on the other hand, a finite-element-based model was used to predict the surface integrity resulting from grind-hardening.

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Keywords: Finite element analysis (FEA), Surface integrity, Grinding, Grind-Hardening

1. Introduction

During manufacturing of high loaded steel parts surface hardening is often achieved by using thermal or thermochemical heat treatment, e.g. induction hardening or case hardening. However, the complex integration of these processes into the production line as well as costs for heat treatment demonstrate the main problems in industry [1].

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For this purpose, the substitution of hardening processes is one of the current developments: “grind-hardening” illustrates an innovative approach for surface hardening and subsequent finishing in one set-up. The grind-hardening process uses the generated heat in the contact zone between the grinding wheel and the workpiece for a short time austenization of the surface layer. The martensitic hardening is mainly induced by self quenching [2] and the use of coolant supply in grinding [3].

Taking the grind-hardening process into account for industrial application, the prediction of achievable hardening depths as a function of process parameters is important, but due to the complex physical interrelationships extensive test series are often required. In this case, modeling and the finite element analysis (FEA) based on experimental results present a solution to reduce time and effort regarding the layout of grind-hardening processes.

The objective of the present paper is to develop a finite-element-(FE)-based simulation for outer-diameter (OD) grind-hardening based on results that are validated by means of experiments.

2. Design of experiments and results for grind-hardening in outer-diameter grinding

The grinding tests were conducted on an Overbeck 600 R CNC-HGS grinder using a corundum grinding wheel of type A80 HH 9V with a width of 10 mm and a diameter of 400 mm. All tests were done in up grinding mode with a wheel speed of v_c = 35 m/s. The cooling conditions were kept constant with a flow rate of Q_{CL} = 25 l/min and the usage of a water based coolant solution. The test specimens made of soft-annealed ball-bearing steel 100Cr6 (AISI 52100) were premachined to a diameter of 58 mm and a width of 20 mm. Based on the examinations of Brockhoff [1] and differing to the work of Nguyen and Zhang [4], the OD-grind-hardening process is divided in two phases. Firstly, the infeed is carried out without workpiece rotation and a plunge speed v_{fr} of 3 mm/min. Afterwards, the process proceeds with a constant depth of cut a_e and a 360-degree rotation of the workpiece. Concerning the second phase, different specific removal rates Q'_w were realized by a variation of depth of cut a_e in a range of 0.5 mm up to 1.0 mm as well as by circumferential speed of workpiece v_w in a way that the residence time of thermal load Δt during grind-hardening corresponds to known values of Δt in surface grind-hardening (Table.1) [5]. The residence time Δt can be calculated by:

$$\Delta t = l_g / v_w \quad (1)$$

where l_g is the geometric contact length [6]. One grinding cycle consists of one revolution of the workpiece. At the point of the workpiece which corresponds to the half of cutting time the process forces and the hardness penetration depth have been evaluated. Previous to each grinding test, the wheel was dressed with a single point diamond dresser using an overlapping rate of U_d = 3.

2.1. Process forces and specific cutting power P_c''

To generate input data for the FE-based simulation several outer-diameter grinding tests were performed in order to measure the process forces. For monitoring the normal process forces a dynamometer is mounted under the grinding wheel spindle. The tangential force F_t has been calculated from the measured normal force by [7]:

$$F_t = \mu \cdot F_n \quad (2)$$

where μ is the force ratio with an assumed value of 0.5 in case of grind-hardening. This assumption is in agreement to experiences in surface grind-hardening and to results published by Stöhr [6]. Based on F_t the specific cutting power P_c'' has been determined by:

$$P_c'' = (F_t \cdot v_c) / (a_p \cdot l_g) \quad (3)$$

where a_p is the width of cut [6]. The values for F_t and P_c'' regarding the different process parameters are shown in Table.1. The results for P_c'' show increasing values with decreasing residence time Δt. This effect is caused by the higher tangential force F_t due to increasing specific removal rate Q'_w. Furthermore, a higher depth of cut a_e and corresponding higher l_g-values causes decreasing values for P_c'', what corresponds to equation 3. In which extend the thermal load generated by the varied specific cutting power was sufficient for grind-hardening was investigated by measurement of hardness and metallographic investigations.

2.2. Hardness profiles and metallographic investigations

In addition to the measurement of process forces, micrographs and hardness profiles were made of each sample's cross-section at 180-degree workpiece rotation. Based on the hardness profiles, the hardening depth (HD) of the workpieces, which is defined by the depth of exceeding a hardness of 550HV0.5 in the middle of the ground groove, has been determined (Table.1). The results show that a surface hardening of the samples has been achieved and the hardening depth increases with higher depth of cut a_e. This effect may result from a higher geometric contact length l_g in case of increasing values for a_e, which affect a larger transient temperature field during grind-hardening. But, a clear and simple correlation between process parameters and hardening depth was not found. That is the reason why it can be expected that the reached hardening depth is a function of residence time Δt, specific cutting power P_c'' and contact length l_g. In further experimental investigations this assumption has to be verified and extended process parameters have to be determined for the variation of the hardening depth in an exceeded range.

Table.1. Process parameters for outer-diameter grind-hardening.

No.	Q'_w [mm³/(mm·s)]	a_e [mm]	v_w [mm/min]	Δt [s]	U_d [-]	F_n [N]	F_t [N]	P_c'' [W/mm²]	HD [mm]
1	3.6	0.5	425.3	0.71	3	185.2	92.6	64.4	0.43
2	1.8	1.0	106.8	4.00	3	152.6	76.3	37.5	0.56
3	2.5	1.0	149.5	2.86	3	158.4	79.2	38.9	0.49
4	3.6	1.0	213.5	2.00	3	190.4	95.2	46.8	0.62

3. FE-based simulation of grind-hardening in outer-diameter grinding

The FE-based simulation of outer-diameter grinding is used to predict the surface integrity resulting from grind-hardening. Therefore, the simulation model has to represent the physical behavior of the actual process. To fulfill these requirements, a thermo-metallurgical model is created, which enables the calculation of the heat distribution within the contact zone area, the transient temperature field within the workpiece as well as the resulting phase transformations in the subsurface layer. The following sections describe the implemented simulation model as well as the validation of the calculated results using the measured hardening depth distributions. The simulations, which are presented and discussed subsequently, are carried out using the software tool "Sysweld" by the ESI Group.

3.1. Simulation model of grind-hardening in outer-diameter grinding

As mentioned above, the aim of the numerical examinations is the calculation of the hardening depth distributions resulting from the heat input and the phase transformations during the grind-hardening process. In this regard, considering the dominant thermo-metallurgical effects, the focus during the model build-up is set on modeling the heat distribution within the contact zone area. Therefore and differing to previous publications [5, 8-11], the transient material removal is considered by a time-dependent deactivation of the finite elements to model the heat flow dissipated by the chips. The heat flow to the coolant and the one to the environment via radiation are modeled by heat transfer coefficients. Concerning the effect of the coolant within the contact zone, a heat transfer coefficient of 0.035 W/(mm^2·K) for a_e = 0.5 mm and of 0.0275 W/(mm^2·K) for a_e = 1.0 mm is implemented. The heat input in the contact zone is realized using state-dependent heat source models, whose heat flux density is multiplied with a heat distribution coefficient of 0.9 to consider that 10% of the grinding power is conducted to the grinding wheel. In Zaeh et al. [5] the modeling of the temperature-dependent material behavior and the implemented methods for the microstructural transformation are presented in detail.

The developed FE-based model is shown in Fig.1. For different process states, the material removal as well as the heat source models are depicted. The degrees of freedom of the FE model are reduced by taking the symmetry relative to the working plane into account. Due to the constant equivalent chip thickness during plunging into the workpiece, a constant heat source model is applied during the plunge process with a heat flux density of 2.48 W/mm^2 for a_e = 0.5 mm and of 3.51 W/mm^2 for a_e = 1.0 mm. Based on Zaeh et al. [5] the heat input during the OD-grind-hardening process is modeled using a linear positive heat source. Therefore, the grinding power is calculated by multiplying the calculated tangential force F_t (see Table.1) with the wheel speed v_c.

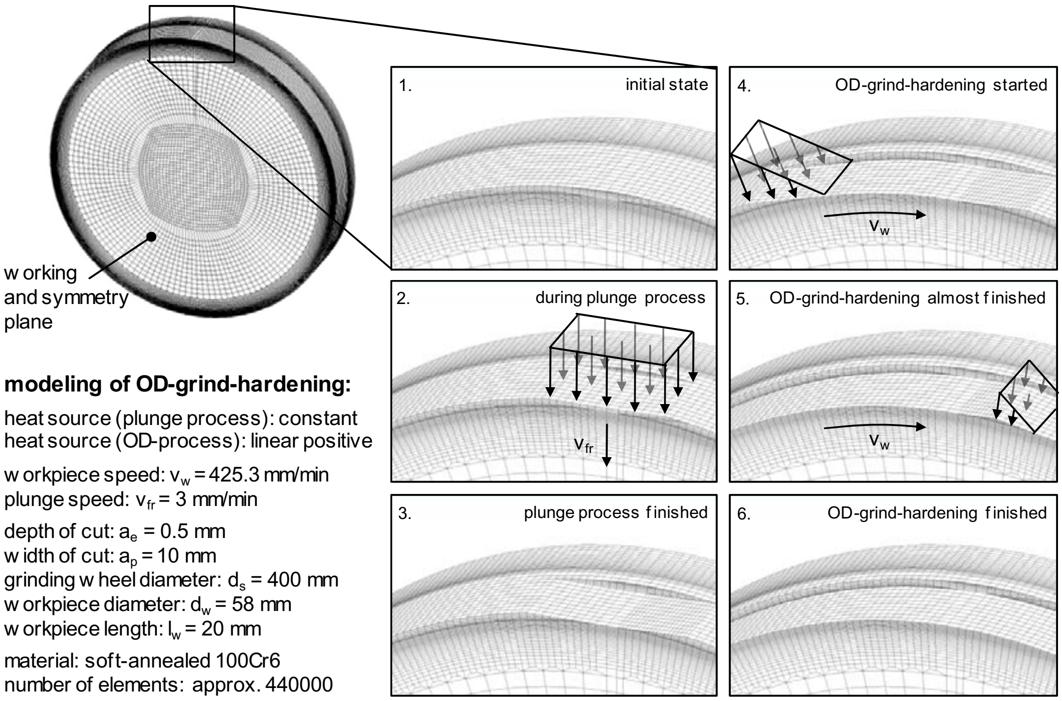

Fig. 1. FE-based model considering the material removal as well as the heat source models for different process states.

3.2. Validation of simulation results

By means of the thermo-metallurgical simulation, the phase transformations and afterwards the hardening depth distribution within the subsurface layer are calculated based on the transient temperature field and the defined material behavior. During the plunge process the simulated temperatures do not exceed a value of 150 °C for all parameter sets, what can be explained by the low plunge speed. The temperature fields of different process states during the OD-grind-hardening process are shown in Fig. 2. After a short starting phase with increasing maximal temperatures, a quasi-stationary temperature field is reached for all parameter sets. By the end of the OD-grind-hardening process the temperature decreases due to the reduction of the geometric contact length.

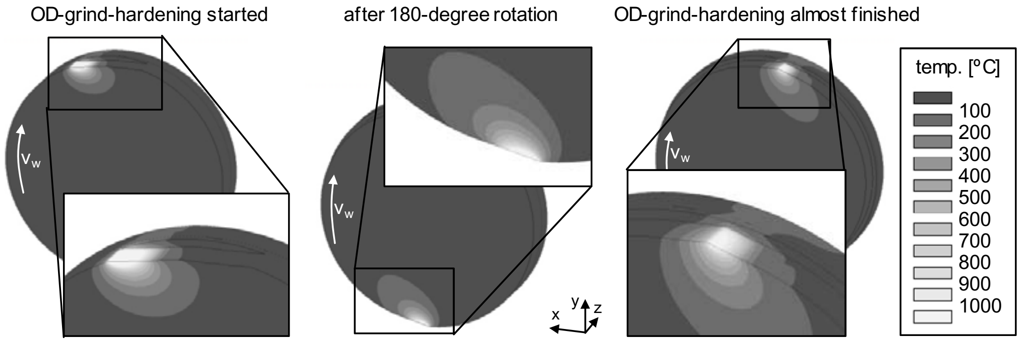

Fig. 2. Temperature fields of different process states considering the material removal (a_e = 1.0 mm, v_w = 213.5 mm/min).

Fig. 3 depicts the validation of the simulated hardening depth distribution after cooling. Based on the low maximal temperature during the plunge process, a hardness slip beneath the plunge area can be determined (Fig. 3 a)). The measured and simulated cross section views normal to the tangential feed direction illustrate consistent hardening depth distributions (Fig. 3 b)). In Fig. 3 c) comparisons of the hardening depths for different parameter sets show results in good agreement. The divergences can be explained by the assumption that the cutting force ratio for calculating the tangential forces is constant over all parameter sets.

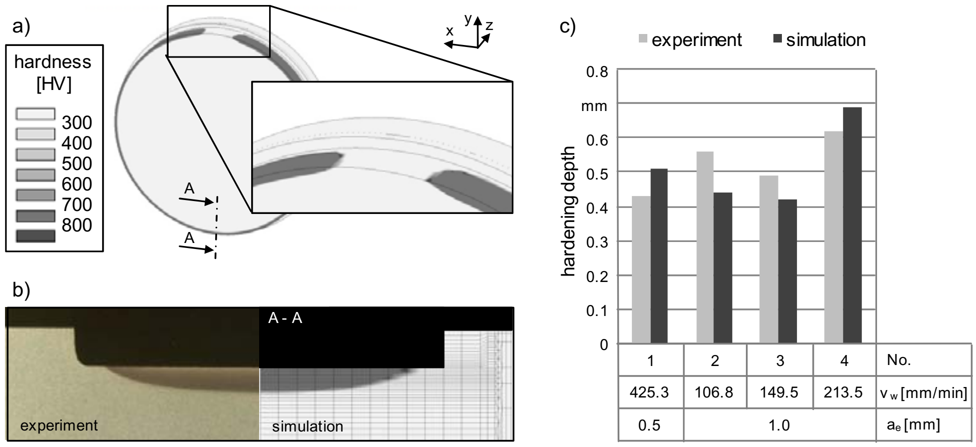

Fig. 3. Validation of the simulated hardening depth distributions after cooling using the measured ones (a_e = 1.0 mm, v_w = 213.5 mm/min). a) Hardening result within the workpiece focused on the hardness slip beneath the plunge area. b) Comparison of the measured (left) and simulated (right) cross section views normal to the tangential feed direction. c) Comparison of the measured and simulated hardening depths within the working plane after 180-degree workpiece rotation for different parameter sets.

4. Summary

This paper discusses the OD-grind-hardening of ball-bearing steel and illustrates the possibility to simulate the resulting surface integrity while considering the material removal within the model. To account for the real process conditions concerning the equivalent chip thickness during the plunge process and the OD-grind-hardening, the heat input is implemented using two different heat source models. Therewith, the FE-based simulation is generally qualified to calculate the transient temperature fields and the hardening depth distributions resulting from OD-grind-hardening.

Future research topics will be the hardness slip and further optimization of the simulation model. To improve the ability of the FE-based simulation, the developed model will be validated again by means of additional measurements of process forces as well as of temperatures within the subsurface layer.

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