Experimental and numerical analysis of residual stress change caused by thermal loads during grinding

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Abstract

A realistic modelling and simulation of the resulting surface integrity e.g. residual stresses caused by grinding is limited due to the lack of knowledge to estimate the amount of thermal load affecting the workpiece. This paper deals with the inverse determination of the heat partitioning during grinding and the prediction of the resulting residual stress state due to the thermal impact by using 2D FEM-simulation without phase transformations. Grinding tests have been performed and the temperatures beneath the contact zone have been measured. For the first time, the concept of Process Signatures is applied on a machining process, providing basic functional relationships for process quantities, internal material loads and material modifications for predominantly thermal loads.

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1. Introduction

The surface integrity in terms of e.g. residual stresses has a strong influence on the functional performance of the manufactured components [1]. Machining processes cause thermal, mechanical and/or chemical loads affecting the surface and subsurface properties of the workpiece material. As a consequence, the modeling and simulation of the resulting surface and subsurface properties after machining has become more and more relevant for current research and industry. Many research activities in the field of numerical [e.g. 2, 3] and analytical [e.g. 4, 5] models for machining processes have been focused on the process layout not reliant on preliminary test series. Regarding the prediction of residual stresses induced during grinding different approaches can be derived from literature [6, 7]. Based on the analytical calculation of surface temperatures and/or temperature fields, Finite-Element-(FE)-based simulations are used to determine the residual stress state within the subsurface area of ground components. In general, the generation of residual tensile stresses during grinding of hardened steel is dependent on specific temperature limits which have to be exceeded at the surface [8, 9] and which are in agreement with the findings by Malkin and Guo [10].

However, the mentioned approaches are process-oriented, correlating changes of surface and subsurface properties with process parameters. The direct selection of machining parameters to achieve a desired surface integrity state is generally not possible [11]. In this regard, the concept of Process Signatures is proposed, enabling a material-oriented view on machining taking into account the acting internal material loads [11, 12]. In this context, Process Signatures describe correlations between the mentioned loads during a certain process and the resulting material modifications.

2. Objectives and procedure

This paper aims to predict the residual stress state change at the surface due to grinding to provide a first approach in generating a Process Signature for a machining process with a
predominant thermal load. In order to reduce the complexity, grinding tests were performed achieving temperatures in the workpiece not higher than the austenitizing temperature. This procedure ensures that no phase transformations occur and the residual stress state will be changed due to thermal load and plastic deformations only. Based on temperature measurement in the subsurface of the workpiece, FE-based simulations were used to determine the heat partition fraction to the workpiece through an iterative approach, as the fraction of grinding power induced into the workpiece cannot be determined by experiments. The calibrated model was used to determine the internal material load state in terms of the quasi-stationary temperature distribution in the workpiece during the process as well as material modifications through the residual stress state resulting from grinding. For validation purposes, the simulated surface residual stresses were compared with measured surface residual stresses acquired after the grinding experiments using X-ray diffraction.

3. Methods

3.1. Workpiece Preparation

For temperature measurements during grinding, thermocouples (diameter 0.25 mm) have been placed into the workpieces at a distance of 2 and 7 mm from the grinding zone. In this regard, the workpieces (length 150 mm, width 29 mm, height 30 mm, AISI 4140 (42CrMo4), normalized state) has been provided with a groove (30 mm length, 11.9 mm height) from the bottom side at the lateral position where the thermocouples were located to ensure machining of the holes by conventional drilling, as well as guiding properly the electric cables out of the machine tool. Distances of the holes’ tip to the workpiece surface have been measured in order to assure a sufficient accuracy for the calibration as well as for the validation of the FEM-model and simulations (Ztc.2mm and Ztc.7mm in table 1).

3.2. Grinding Experiments

A corundum grinding wheel type 9A60D28VCF2 with a width of 30 mm and 400 mm in diameter has been used at a constant wheel speed of \( v_s = 35 \text{ m/s} \). As maximum contact zone temperatures above \( AC_1 = 750 \text{ °C} \) (conversion temperature) should be avoided, a very low specific removal rate of \( Q_{sw} = 1.5 \text{ mm}^3/(\text{mm} \cdot \text{s}) \) has been set constant for the experiments whereas the depth of cut \( a_e \) and the tangential feed speed \( v_{ft} \) have been varied (table 1).

3.3. Finite Element Model

The process was modelled as a 2D uniform moving band heat source in the FEM-Software DEFORM (Fig. 1). The grinding operation itself was not modelled, the mechanical impact of the process was therefore neglected. Input parameters for the heat source were derived from the experimental setup, providing \( v_n \) as moving speed of the heat source and \( I_q \) as heat source length:

\[
I_q = \sqrt{\frac{2}{\pi} \cdot \frac{4}{Q_{sw}} \cdot \frac{a_k}{\beta}}
\]

The heat source intensity (heat flux) \( q \) was modelled as a fraction of the grinding power, measured in the experiments:

\[
q = k_w \cdot P_e^{0.5}
\]

An initial simulation with a rough estimation of the half specific grinding power \( k_w = 0.5 \) is provided as input (heat flux) for the simulation (Fig. 2). The maximum temperature difference at \( Z_{tc.2mm} \) between simulation and measurement was used to adjust the heat flux until the criterion \( \Delta \theta < 1 \text{ °C} \) was achieved.

| Test series | \( Q_{sw} \) [mm³/(mm·s)] | \( a_e \) [mm] | \( v_{ft} \) [m/min] | \( Z_{tc.2mm} \) [mm] | \( Z_{tc.7mm} \) [mm] |
|-------------|-------------------------|----------------|----------------|--------------------|--------------------|
| 1           | 1.5                     | 0.02           | 4.500          | 1.931              | 6.926              |
| 2           | 1.5                     | 0.04           | 2.250          | 1.883              | 6.836              |
| 3           | 1.5                     | 0.06           | 1.500          | 2.025              | 7.078              |
| 4           | 1.5                     | 0.08           | 1.125          | 1.871              | 6.904              |
| 5           | 1.5                     | 0.10           | 0.900          | 1.945              | 6.935              |

Fig. 1. Schematic overview of the used model, parameters and boundary conditions

Fig. 2. Determination of the optimized heat partition fraction to the workpiece \( k_w \)

The heat partition to the environment was set to 100 W/(mm·K). Thermophysical properties were modelled according to [13], stress strain curves for temperatures up to 750°C were measured with a strain rate of approximately \( 3 \cdot 10^{-3} \text{ s}^{-1} \) and were used to model the plastic behavior. To
reproduce the magnetic clamping used in the experimental setup, the nodal displacements of the bottom side of the workpiece were set to zero. The nodal temperature at the bottom was kept constant at \( \Theta \approx 20 \) °C. Residual stresses where determined after a relaxation period of the workpiece temperature to 20 °C.

Malkin and Guo showed that the maximum temperature has a significant influence on the surface and subsurface properties and can be expressed as a function of the heat flux to the workpiece and the contact time [10]:

\[
\Theta_{\text{max}} \sim q \cdot \sqrt{\Theta_c}.
\]  

(3)

Using the calibrated simulations, the maximum temperature at the grinding contact can be determined. For the concept of Process Signatures, this approach can be used to develop a functional relationship between thermal internal material loads (max. temperature, max. temperature gradient) and process quantities \((q, \Theta_c)\). Thus, the Process Signature for predominantly thermal loads can be developed, correlating material modifications (surface residual stresses) with the investigated internal material loads.

4. Results

4.1. Heat partition fraction to the workpiece \( k_w \)

In Fig. 3 the resulting maximum temperature at \( Z_{tc.2mm} \) in the simulation for several heat partition fractions is shown exemplarily for sample 4 of the test series. The iterative approach reveals a linear dependency of the maximum temperature at the measuring height from the heat partition fraction \( k_w \) and thus, naturally on the input heat flux.

\[
\Theta_{\text{max}} = \Theta_{\text{max}} (0.4, 0.5, 0.7) \text{ MPa}.
\]

Fig. 3: Simulated maximum temperatures at \( Z_{tc.2mm} \) versus \( k_w \)-factor for test setup 4

4.2. Correlation of process quantities with internal material load

Fig. 4 shows the maximum surface temperature and the maximum temperature gradient perpendicular to the workpiece surface \((x\)-direction) determined by the simulation for the test series. As expected, with rising \( q \cdot \sqrt{\Theta_c} \) values the heat input at a surface point increases, which causes an increasing temperature rise beneath the workpiece surface as proposed by Malkin and Guo [10]. An almost linear functional behavior for the internal material load \( \Delta \Theta_{\text{max}} \) due to process quantities can be determined. The simulated maximum temperature gradient shows an unsteady behavior at higher \( q \cdot \sqrt{\Theta_c} \)-values. In order to exclude an erroneous influence of the FE-Model, the temperature gradient was additionally investigated through an analytical approach based on Carslaw and Jaeger [13] which leads to similar results. The temperature gradient profile is therefore seen as accurate and further experimental data must be supplied in order to determine a functional relationship with process quantities.

Fig. 4: Maximum surface temperature and gradient due to the heat flux to the workpiece and the contact time

4.3. Correlation of internal material loads with material modifications (Process Signature)

Fig. 5 provides the measured and simulated residual surface stresses on the simulated maximum surface temperature occurring during the grinding process. It can be seen that simulation results qualitatively agree with the measurements, shifted by a constant value. For low maximum temperatures, residual compressive stresses can be observed after the experiments. As the process model includes thermal loads only, the mechanical influence due to the chip formation in the grinding zone was not taken into account. However, the offset for the whole test series is almost constant \((\Delta \sigma_{\text{offset}} = 170 \text{ MPa})\).

For the measured residual surface stresses parallel to the grinding direction \( \sigma_{\|} \), the functional relationship with \( \Theta_{\text{max}} \) can be expressed as a polynomial regression:

\[
\sigma_{\|} = -0.002971 \cdot \Theta_{\text{max}}^2 + 3.623 \Theta_{\text{max}} - 644.9
\]

(4)

with \( \Theta_{\text{max}} < AC_1 \) (750 °C). \( R^2 = 0.9996 \).

Fig. 5: Surface tangential residual stress depending on the maximum surface temperature

The residual stress over the occurring temperature gradient (Fig. 6) delivers the same offset as seen in Fig. 5. Fig. 6 shows that obviously a specific threshold for the maximum gradient must be achieved in order to generate residual stresses, but a further increase of the gradient does not deliver higher stresses. In order to provide a functional relationship further
investigations in the range of $\partial \sigma_{\text{max}} / \partial z = 0.1 – 0.25 \text{K/}\mu\text{m}$ are necessary.

![Graph showing simulated and measured tangential residual stress versus simulated maximum temperature gradients at the surface.](image)

Fig. 6: Simulated and measured tangential residual stress versus simulated maximum temperature gradients at the surface

5. Conclusion

By the presented simulation approach, correlations between the internal material loads and the material modifications (Process Signature) can be achieved. Thermal material loads during the process below the austenitizing temperature and resulting residual stresses in dry grinding are determined via Finite Element simulations, based on moving heat source modelling. The fraction of heat induced into the workpiece due to grinding energy can be determined by temperature measurements. The knowledge of the heat partition fraction enables the determination of the temperature distribution in the workpiece and resulting residual stresses. Neglected mechanical loads in the model might be the reason for the observed constant offset in residual stresses. Finally, a functional relationship between the maximum surface temperature and residual surface stress in grinding direction for temperatures below the austenitizing temperature is given. This work provides a basic approach to establish Process Signatures for processes with predominantly thermal loads. In future work, the inclusion of phase transformations will be investigated for the grinding process to provide functional relationship above the austenitizing temperature.

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Nomenclature

- $a$: depth of cut [mm]
- $d$: grinding wheel diameter [mm]
- $k$: heat partition fraction to the workpiece [-]
- $l$: geometric contact length in grinding [mm]
- $R$: specific grinding power [W/mm²]
- $q$: heat flux to the workpiece [W/mm²]
- $Q$: specific material removal rate [mm³/(mm·s)]
- $R^2$: coefficient of determination [-]
- $t$: contact time [s]
- $v$: tangential feed speed [m/min]
- $v_s$: grinding wheel speed [m/s]
- $\delta$: distance of the thermocouple from the surface [mm]
- $\sigma$: residual stress parallel to grinding direction [MPa]
- $\theta_{\text{max}}$: Maximum temperature [°C]
- $\partial \sigma_{\text{max}} / \partial z$: Maximum temperature gradient [K/µm]