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Material modifications caused by thermal and mechanical load during grinding

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Abstract

This paper discusses results acquired during surface grinding experiments performed on hardened steel workpieces. The experimental results show different zones of thermally induced material modifications during grinding depending on the contact time Δt and the maximum contact zone temperature T_{max}. In particular it was observed that rehardened zones occurred within two separated ranges of temperatures and contact times. Further analyses revealed that these separated time and temperature ranges correspond to significantly different mechanical loads as well as to varying retained austenite rates. The experimental results shall help to identify possible mechanisms responsible for the observed material modifications during grinding.

Keywords: Grinding, Residual stress, Surface integrity, Thermal effects

1. Objectives and general research approach

The grinding process can be considered as an external short-time local thermo-mechanical load on the workpiece surface [1]. This load results from the engagement between the ground workpiece surface and the single abrasive grains at the surface of the grinding wheel. Due to the high velocity and the multiplicity of the abrasive grains, the external workpiece surface load can be characterized by local „flash" temperatures and grinding forces [2]. This would imply local peak temperatures and stresses near the workpiece surface as well. However, experimental investigations, for example according to [3], indicated rather continuously increasing temperatures and stresses beneath the workpiece surface. The determination of internal thermal loads has been subject to numerous investigations, since it primarily affects the resulting surface layer properties of the ground workpiece [1, 4, 5].

This paper refers to long-term research efforts aiming at the identification and the prediction of the internal thermal and mechanical material load during the grinding process. It is intended to correlate the internal material load to the modifications of workpiece surface layer properties after grinding (referred to as material modifications after [1]) by a physical based approach.

Since the thermal load during grinding primarily limits the workpiece quality (due to the onset of grinding burn), the focus of the experiments was laid on identifying the thermal load first. In previous investigations reported in [6], an approach based on the known TTA- and TTT-diagrams from the conventional heat treatment provided promising results. This approach is based on mapping the resulting material modifications over the maximum contact zone temperature T_{max} and the contact time Δt. This leads to the so called T_{max}-Δt-diagram (cf. figure 1). The contact time Δt can be calculated according to the following expression:

$$\Delta t = \frac{l_g}{v_{ft}}, \qquad (1)$$

where l_g denotes the geometric contact length and v_{ft} denotes the tangential feed speed. The primary purpose of the T_{max}-Δt-diagram is to achieve targeted material modifications after grinding by means of in-process temperature monitoring.

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When established, the application of the T_{max}-Δt-diagram saves additional experiments which would be necessary to find a suitable process layout leading to the desired material modifications.

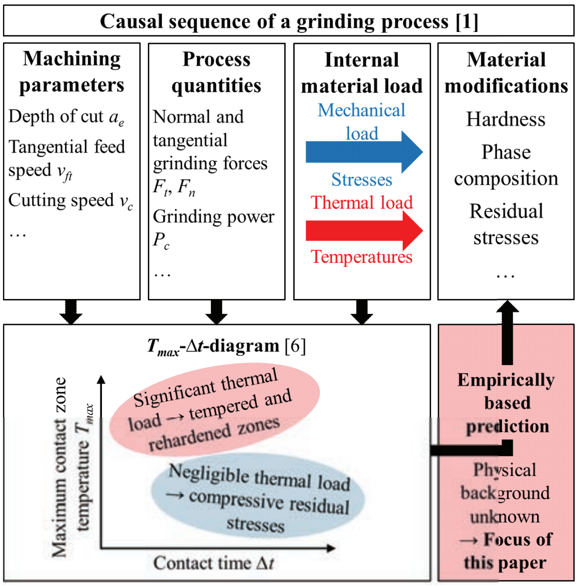


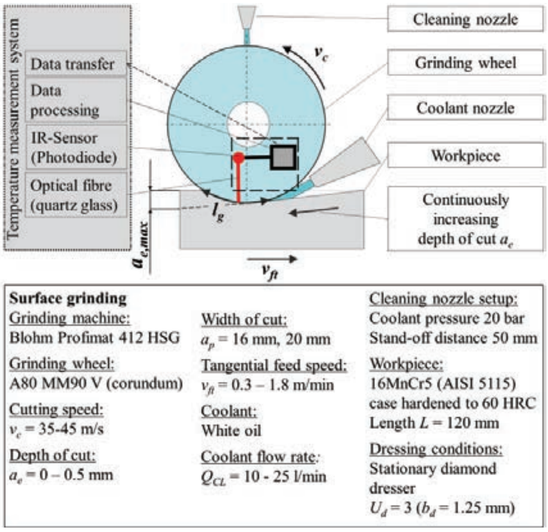
Fig. 1. T_{max}-Δt-diagram - a simplified empirical approach to predict material modifications after grinding.

In the following sections, a new T_{max}-Δt-diagram for the workpiece material 16MnCr5 (AISI 5115) identified during surface grinding experiments is discussed. This discussion goes along with considerations referring to the possible phase transformations due to the internal thermal material load as well as to the mechanical load during grinding. These considerations shall help to understand the physical background of the material modifications mapped in the presented T_{max}-Δt-diagram.

2. Experimental results

In order to identify the T_{max}-Δt-diagram for 16MnCr5, a series of surface grinding experiments was performed (cf. figure 2). In order to investigate an interval of T_{max}-values and Δt-values which should be as large as possible, the depth of cut a_e was increased up to its maximum value during a single experiment (v_{ft} was being held constant). A further extension was achieved by performing multiple experiments with different tangential feed speeds v_{ft} and with different coolant flow rates delivered by the coolant nozzle. In order to reduce the effect of grinding wheel clogging and to enhance the reproducibility of the grinding experiments, an additional high pressure cleaning nozzle was used.

During each grinding experiment, the maximum contact zone temperature T_{max} was measured by a temperature measurement system as introduced in [7]. This system is based on the evaluation of the infrared radiation emitted by the ground workpiece surface within the contact zone. A part of the infrared spectrum (wavelength between 2 µm and 4 µm) is transferred to the IR-photodiode which transforms it into an electrical signal. The electrical signal is pre-processed and the values of T_{max} are sent wireless to the external computer. The measured T_{max}-values allow a comparison of the thermal load during grinding resulting from different process layouts. A direct correlation between the measured T_{max}-values and the actual workpiece temperatures during grinding is difficult [7], since the exact emissivity of the ground workpiece surface within the contact zone as well as the effect of grinding chips on the T_{max}-values are currently unknown. Therefore, in this paper, arbitrary units for T_{max} are used.



Surface grinding
Grinding machine:
Blohm Profimat 412 HSG
Grinding wheel:
A80 MM90 V (corundum)
Cutting speed:
$v_c = 35\text{-}45$ m/s
Depth of cut:
$a_e = 0 - 0.5$ mm

Width of cut:
$a_p = 16$ mm, 20 mm
Tangential feed speed:
$v_{ft} = 0.3 - 1.8$ m/min
Coolant:
White oil
Coolant flow rate:
$Q_{CL} = 10 - 25$ l/min

Cleaning nozzle setup:
Coolant pressure 20 bar
Stand-off distance 50 mm
Workpiece:
16MnCr5 (AISI 5115)
case hardened to 60 HRC
Length $L = 120$ mm
Dressing conditions:
Stationary diamond dresser
$U_d = 3$ ($b_d = 1.25$ mm)

Fig. 2. Process layout of the performed surface grinding experiments.

The ground workpieces were analyzed by means of Barkhausen noise measurement, X-ray diffraction measurement as well as hardness measurement and metallographic inspection. In correspondence with previous work focused on the material modifications after grinding (for example [8]), areas of similar material modifications were defined (cf. table 1). The changes $\Delta\sigma_{RES}$ of resulting tangential surface residual stresses (referred to as residual stresses in the following sections) were calculated by considering the depth profile of residual stresses before grinding. Other criteria were the full width at half maximum FWHM resulting from the X-ray measurement, the Barkhausen noise level (BH), the hardness and optical micrographs.

By coupling the information on resulting material modifications with the measured T_{max}-values and the calculated Δt-values, the T_{max}-Δt-diagram for 16MnCr5 was established (see figure 3). The areas in this diagram are highlighted by a color code according to table 1.

It was found that the thermal impact of the grinding process may be kept minimal at contact times between 0.5 and approximately 1.20 s. By short contact times (below 0.50 s) and longer contact times as well (over 1.20 s), a stronger thermal impact was detected leading to tensile residual stresses. This corresponds to practical experience in grinding of various case hardened steels and reveals that choosing short contact times (which means lower depths of cut or higher tangential feed speeds) does not always ensure a „burn-free" grinding process. At higher contact zone temperatures, tempered zones were detected for almost the entire range of investigated contact times.