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Surface and material modifications of tempered steel after precision grinding with electroplated coarse grained diamond wheels

C. Heinzel[a,b]*, F. Borchers[a,b], D. Berger[a,b], L. Ehle[c]

[a]*Foundation Institute of Materials Science, Division Manufacturing Technologies, Badgasteiner Straße 3, 28359 Bremen, Germany*
[b]*University of Bremen and MAPEX Center for Materials and Processes, Bibliothekstraße 1, 28359 Bremen, Germany*
[c]*Central Facility for Electron Microscopy, RWTH Aachen University, Ahornstraße 55, 52074 Aachen, Germany*

* Corresponding author. Tel.: +49-421-218-51110; fax: +49-421-218-51102. *E-mail address:* heinzel@iwt.uni-bremen.de

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Abstract

One particular kind of engineered grinding wheels are precisely profiled grinding tools with flattened coarse diamond grains, primarily used for machining of brittle materials. Because of their grain geometries, they are also expected to introduce mechanical strains into steel workpieces generating a work hardening effect. Also low surface roughnesses combined with favorable compressive residual stresses are targeted. In this paper the feasibility of this process technology is investigated and possible adverse aspects are identified. These findings can be used in future to further develop the process towards higher forces and speeds and thus conditions close to industrial applications in conventional grinding of steel parts.

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1. Introduction and research approach

Grinding processes have primarily thermal and mechanical impacts on the material, which have effects on the surface integrity and the material modification of manufactured parts. Thermal impacts have, besides of exceptions such as grind-hardening [1], generally negative effects on the surface properties [2] while mechanical impacts in certain processes can be used to improve the properties of the surface and the subsurface layer [3]. The significance, which each of those impacts has, depends inter alia on the process design. Hence the choice of process parameters can be done in a way that the mechanical impact is predominant and the thermal influence can be neglected. Important parameters are low cutting speeds v_c and low chip thicknesses h_{cu} [4]. In materials like steel alloys, which show a strain-hardening effect, this can generate positive material modifications within the surface and subsurface layers due to the size effect in grinding leading to the so-called grind-strengthening [4].

However the increase of hardness as well as the depth of the induced compressive residual stress that was achieved with this method was comparably low. The approach presented here aims at improving this situation by working with special grinding tools which originally were designed to machine hard and brittle materials primarily in a ductile mode by inducing comparably high pressure in normal direction to the surface during the grinding operation. In this paper it is examined, if these tools are also able to induce a mechanical impact into steel workpieces (AISI 4140) that leads to an increased grind-strenghtening effect. Also the wear behavior of the diamond when machining steel with low temperatures and high pressure in the contact zone is investigated.

A new approach to characterize the correlations of material modifications independent from the process only by the internal material loads is called Process Signatures [5]. With the resulting transfer functions the mentioned dependencies can be described and used for a desired, surface properties driven process design.

To generate the engineered grinding wheels with flattened coarse diamond abrasives, a special dressing technology is used. The expression “engineered” characterizes the (quasi-) deterministic behavior of the tool, meaning that the macro and micro topography has to be generated and known precisely. A prerequisite for deterministic ultra-precision grinding is a

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uniform protrusion height of the abrasive grains [6]. This is achieved by flattening the coarse diamond grains, which is expected to generate a hydrostatic pressure in the contact zone [7]. These wheels can be applied for precision ductile grinding of different brittle materials. Roughness values Ra of 15.47 nm and PV of 104.1 nm were achieved by ductile-regime grinding of the material borosilicate glass (BK7) [8].

2. Experimental Setup and Procedure

2.1. Dressing procedure and wheel specification used

The dressing of the coarse-grained, single-layered diamond tools with electroplated bond can be performed by a mechanical-abrasive dressing process, with a rotational diamond abrasive dresser [9] and by a thermo-chemical dressing process. Both dressing techniques are performed once before grinding. The disadvantage of the mechanical-abrasive process is the long duration. For that reason, a subsequent thermo-chemical dressing process has been established [10]. This dressing technique is based on dynamic friction polishing. Fig. 1 shows the set-up for thermo-chemical dressing of engineered grinding wheels.

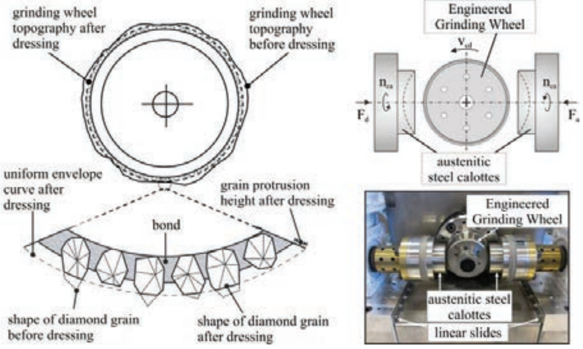

Fig. 1. Engineered wheel with flattened coarse grains and thermo-chemical dressing process

Two rotating austenitic steel calottes, mounted on two linear axes and powered by geared motors, are pressed against the grinding wheel with a certain force. The force is applied from two sides in order to avoid a torque on the grinding wheel. The dressing process lasts for about 3 hours and is monitored by an acoustic emission sensor, maintaining a uniform dressing process. More details are given in [10].

The specification of the used engineered grinding wheel is listed in table 1. The grinding wheel's body is made of high-alloyed austenitic steel and is manufactured by precision turning, with an accuracy lower than 2 µm. Due to the coarse grains and the hard bond, these tools exhibit a high wear resistance. With the above mentioned dressing technique, only a fraction of the bonded diamond grains are flattened down and are in contact with the workpiece during the grinding process. For the D301-tool there are roughly about 150 grains around the whole circumference of 236 mm which have been visibly dressed and are in contact. The other grains are not protruding high enough to be in contact with the dressing tool.

Table 1. Applied engineered grinding wheel

Wheel specification	Values
Average grain size	301 µm (D301)
Concentration	C100, single-layered
Bond	Electroplated
Diameter	75 mm
Width	3.5 mm
Profile	Spherical (radius 37.5 mm)
Active grit concentration	15 grains/mm^2 (D301)

2.2. Machine tool and force measurement

Grinding experiments were carried out on the 5-axis ultra-precision grinding machine tool Nanotech 500 FG. The machine tool features high stiffness in axes and spindles and high motion accuracies. Within the machine tool, a dynamometer (Kistler Type 9254) is integrated for monitoring normal, tangential and feed forces during the process. The dynamometer is mounted under the grinding spindle and measures the forces by four piezoelectric crystals.

2.3. Workpiece material

For all investigations cylindrical workpieces with a height of 25 mm and 60 mm in diameter made from steel alloy AISI 4140 (42CrMo4) were used. The material was heat treated (quenched and tempered) to three different states according to table 2. Afterwards the workpieces were conventionally ground by a flat surface grinding process with a vitrified grinding wheel to achieve a uniform surface and consistent initial conditions.

Table 2. Heat treatment states of the experimental material

denomination	tempering	resulting surface hardness
QT 50	300°C (2h)	50 HRC
QT 33	540°C (2h)	33 HRC
QT 21	650°C (2h)	21 HRC

2.4. Experimental procedure

The process for the material modification investigation is performed as single stroke grinding experiments comparable to flat surface grinding. The most important varied parameters are the cutting speed v_c, circumferential wheel speed v_s respectively, depth of cut a_e and tangential feed velocity v_{ft}. The tangential (F_t) and normal (F_n) forces are considered as external material loads and taken into account as indicators for the induced mechanical energy. The feeds and speeds are indicated in fig. 2. The varied process parameters are listed in table 3, first column. The maximum a_e was investigated in preliminary experiments. To characterize the depth of material modification, metallographic cross-sections of all ground tracks from this parameter study were analyzed. The samples with a visible modification in the surface layers were investigated by hardness measurements and the samples with the highest hardness-increase were investigated by X-ray diffraction and electron backscatter diffraction pattern (EBSD) analysis. For the investigations on wear and roughness, the process was executed with a rotational