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Influence of the macro-topography of grinding wheels on the cooling efficiency and the surface integrity

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Abstract

The surface integrity of ground workpieces is not only influenced by the chosen parameters, but also by the coolant supply. Coolant supply in grinding is mainly governed by the nozzles used and their parameters. However, the cooling efficiency in grinding can also be enhanced by altering the macro-topography of the grinding wheel itself. In this paper three different grinding wheels using the same nozzle parameters are compared with respect to their cooling efficiency and hence their impact on the surface integrity of the ground workpieces. Besides a standard grinding wheel with continuous layer, a slotted grinding wheel as well as a segmented grinding wheel are presented and their respective cooling efficiency is evaluated. It is shown that by altering the macro-topography of a grinding wheel the resulting surface integrity can be influenced positively as well as negatively.

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1. Introduction

Although grinding requires a high amount of energy to remove a specific amount of material compared to cutting processes, the process cannot be substituted due to the achievable workpiece quality [1]. Besides the workpiece quality, mainly defined by the quality of shape and the roughness, the surface integrity is crucial for the performance of the ground parts during their usage. The surface integrity highly influences maximum loads and long-term loading capacities. The surface integrity is, besides mechanical loads, highly influenced by the thermal loads during machining. In grinding, this is especially crucial, as most of the aforementioned energy is converted into heat, due to the high amount of friction. For this reason, cooling and lubrication is of high importance in grinding. The coolant supply in grinding is mainly governed by the nozzle used and their parameters (flowrate, exit speed, positioning) [2]. Besides the optimization of the nozzle parameters, the cooling efficiency is also highly influenced by the macro-topography of the grinding wheel [3].

In this paper, three different high-performance grinding wheels, a standard wheel with continuous layer, a slotted grinding wheel and a segmented grinding wheel, are presented and their respective cooling efficiency is evaluated. It will be shown that by altering the macro-topography of a grinding wheel the resulting surface integrity can be influenced positively as well as negatively.

2. Experimental Setup

The experiments were conducted by means of surface up-grinding using a high performance grinding machine at grinding wheel speeds of 63 m/s. The workpiece material was hardened heat treated steel AISI 4140 (635 HV 0.3), with a width of 20 mm. The coolant used was mineral oil (Petrofer Isocut R 10-H).

Three different high-performance grinding wheels with steel body were examined (diameter 400 mm).

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While all provided the same electroplated B251 abrasive layer, they differed with respect to the macro-topography of the body. Besides a standard high-performance wheel with continuous layer and unaltered body (Fig. 1 a,), a slotted grinding wheel (Fig. 1 b,) and a segmented grinding wheel (Fig. 1 c,) were analyzed.

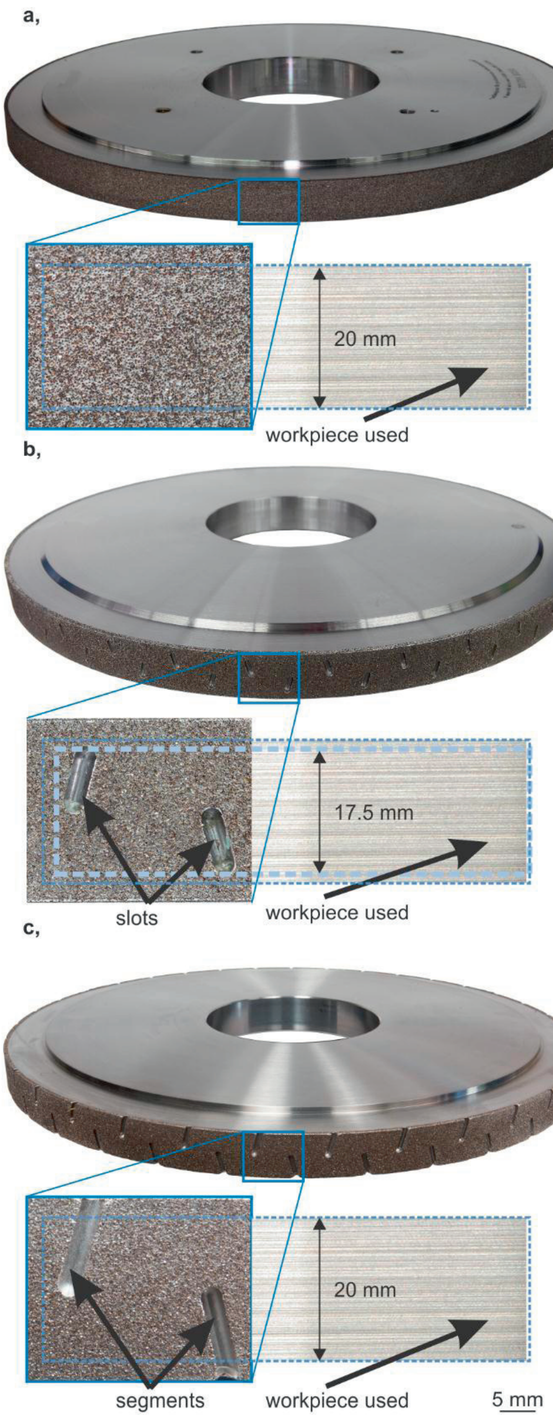

Fig. 1: Grinding wheels used: a, standard; b, slotted; c, segmented

The slotted grinding wheel, as described in [3; 4], provided a total of 70 slots, milled into the wheel periphery, shifted symmetrical alongside the centerline of the grinding wheel axis, slightly rotated by an inclination angle of 15°. The aim of the development of this wheel was to increase the amount of coolant delivered into the contact zone. The width of the slots was kept small (9 mm) to restrict the slots to the width of the workpiece. In doing so, the coolant was to be captured inside the slots to not escape to the sides.

The segmented grinding wheel also provides 70 segments milled into the wheel periphery. The geometry of the segments corresponds to those of the slots of the slotted grinding wheel in terms of depth (2.5 mm), thickness (3 mm) and inclination angle (15°). However, in contrast to the slots, the segments were milled continuously from the centerline of the body to the edge of the body. As a result, the coolant can escape to the sides of the wheel, as described in section 3.

All grinding wheels were operated using the same nozzles and the same nozzle parameters. For cooling, a common free-jet nozzle was used at 105 l/min (a flow-controlled system was used instead of a frequency-controlled, hence a no supply pressure is given here). In addition, a cleaning nozzle, located above the respective grinding wheel, was used at 105 l/min to clean the chip space and to extinguish sparks. The parameters of the cooling nozzle can be found in Fig. 2. The most important parameter, the exit velocity of the cooling nozzle, defined by the interaction of the exit diameter of the nozzle and the flow rate, was 61.2 m/s. This velocity was close to the examined wheel speed, to penetrate the air boundary layer around the wheel periphery and to assure an effective coolant supply [5].

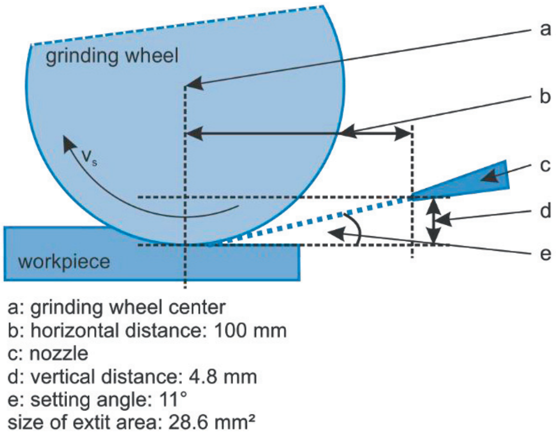

Fig. 2: Nozzle parameters

Five parameter combinations were investigated. At a feed rate of 1000 mm/min, depths of cut of 0.50, 0.75 and 1 mm were applied. This facilitated the examination of the influence of rising material removal rates at constant times of heat impact. To evaluate the influence of the feed rate, 1000, 2000 and 3000 mm/min were applied, each at a depth of cut of 0.50 mm. In doing so, the influence of the time of heat impact with constant amount of removed material could be evaluated.

The impact on the surface integrity is governed by mechanical and thermal loads during grinding [6]. In high-performance grinding, the thermal loads prevail and can lead to tempered and rehardening zones. To identify the impact on the surface integrity in this study, cross-sections of the ground workpieces were prepared and polished. Such a cross-section with rehardening and tempered zones is depicted in Fig. 3.

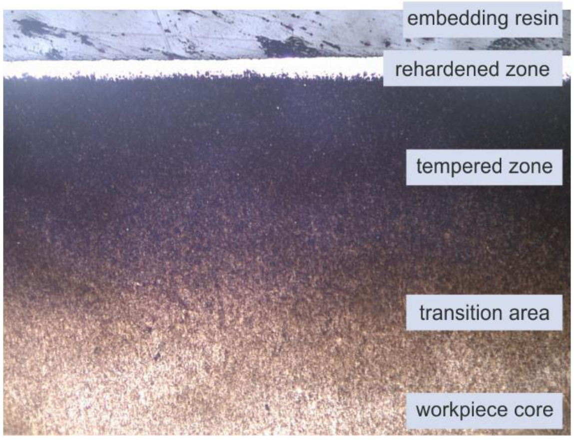

Fig. 3: Etched cross-section of a workpiece with rehardening and tempered zones

Rehardening zones of the etched cross-sections appear white under the microscope and provide a sharp transition to the tempered zone. Due to this, they can be measured reliably via optical microscopes. In contrast, the transition from the tempered zone to the workpiece core is blurred and was hence identified by means of microhardness measurements. The threshold value used to identify the transition from tempered zone to workpiece core was 500 HV 0.3. This corresponded to 80% of the core hardness, a threshold commonly used to determine the hardening penetration depth of heat treatments.

An exemplarily measurement of one workpiece is depicted in Fig. 4. For the evaluation of the grinding wheels in section 3, the depth of alteration of surface integrity at the threshold value was used. The measurements were taken from the middle of the workpieces in relation to their longitudinal and lateral axis. This position corresponds to the stationary grinding regime. The measurements were repeated thrice for each parameter combination and grinding wheel respectively; the resulting standard deviations σ of the values can be found in the respective figures.

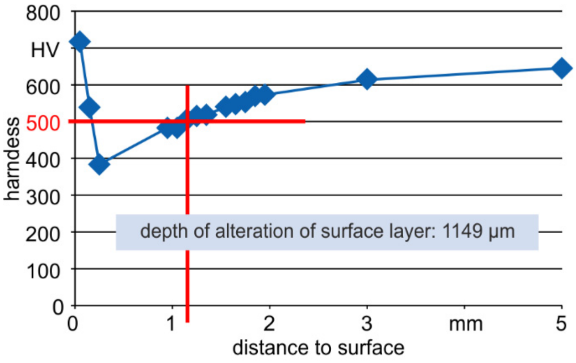

Fig. 4: Microhardness measurement of an exemplarily workpiece

3. Experimental Investigations

The depth of the rehardening zones and the depth of the alteration of surface integrity in dependence of the grinding parameters and the grinding wheel can be seen in Fig. 5. The results clearly show that the macro-topography of a grinding wheel highly influences the cooling efficiency and hence the impact on the surface integrity of the ground workpieces. The highest depths of alteration of surface integrity occurred for the segmented wheel, even resulting in rehardening zones, while the slotted wheel only resulted into a small depth of 102 µm at the maximum feed rate of 3000 mm/min.

In general, the cooling efficiency of the slotted wheel is far better than that of the two other wheels, while the cooling efficiency of the segmented wheel is even worse than that of the standard wheel. The better performance of the slotted wheel can be led back to the additional amount of coolant transported through the slots. The total amount of coolant transported though the contact zone is at least 2.4 times that of the standard wheel, referring to calculations of the theoretical maximum amount of coolant that can be transported through the chip space of an electroplated layer and the amount additionally delivered through the slots, see [3]. Assuming that only half the theoretically possible amount is transported through the chip space, because of the intricacies of transporting coolant through the chip space of a grinding wheel, and at the same time that the full amount of coolant that can be transported through the slots is actually achieved, the total amount of coolant transported through the contact zone by the slotted wheel is 4 times that of the standard wheel. This explains the superior cooling efficiency of the slotted grinding wheel.

For the segmented wheel, the theoretically possible amount of coolant that can be transported through the contact zone is even higher than that of the slotted grinding wheel (as the segments are larger than the slots). However, while the slots are limited to the workpiece width, the segments cover the whole width of the grinding wheel, as common for segmented wheels. As a consequence, the coolant in the segments can, in contrast to the coolant in the slots, escape to the sides. In fact, due to the high rotary frequency of the wheel, the coolant is accelerated to the sides away from the contact zone. In addition, the coolant in the segments, if any, is under ambient pressure. Ultimately, the coolant pressure is not only low in the contact zone, but also in the lubrication gap, as it can escape into the segments and from there to the sides. As shown in previous works [7], a high coolant pressure is of high importance for an efficient cooling, as the results of this study confirm again.

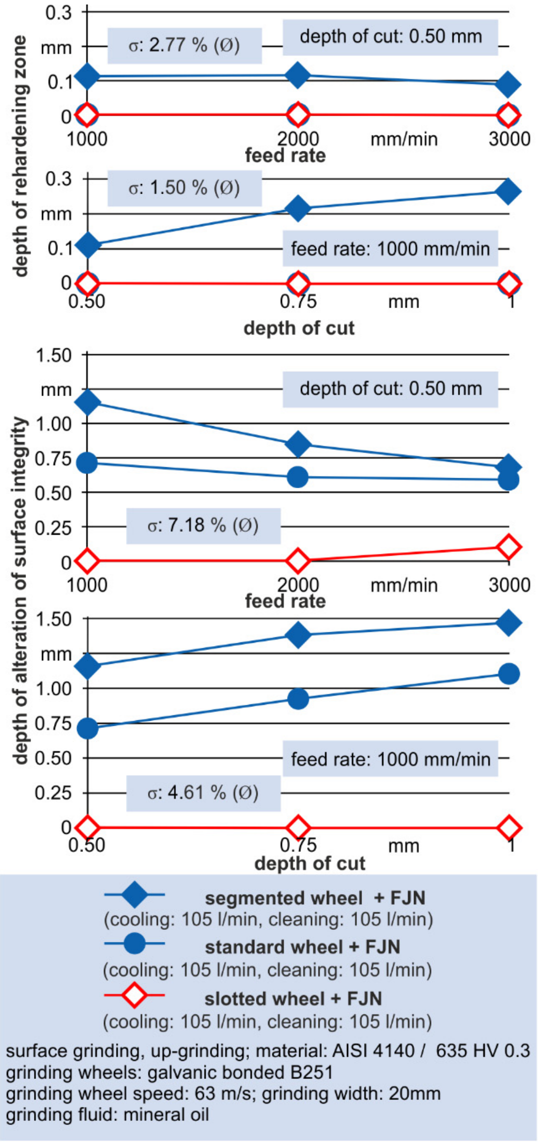

Fig. 5: Alteration of surface integrity

The alteration of surface integrity reflects the thermal load during the process. The thermal load is defined by the machining heat and the duration of heat impact. The machining heat is derived from the process parameters. Rising depths of cut at constant feed rates result into rising machining heat. Rising feed rates (especially at constant depth of cut) result into rising chip thicknesses and hence higher loads of the single grains. This in turn leads to a higher intensity of the thermal load. On the other hand, higher feed rates result into lower durations of heat impact. That means a shorter time, in which the heat can flow into the workpiece, but then again a shorter time for cooling of the workpiece by forced convection.

These general considerations can be applied to explain the results of this study. The same abrasive layer was used for all wheels. Owing to the slots, the slotted grinding wheel provides 7 % less layer than the standard wheel with continuous layer, related to the width of cut. The segmented wheel provides 8.5 % less. A reduction of the abrasive layer is applied for engineered grinding wheels (e.g. [8]). For those, the number of rubbing and ploughing grains is to be reduced to obtain a more efficient material removal process. However, the reduction of static grains is much higher for engineered grinding wheels than for the slotted and the segmented wheel and in addition, a uniform distribution of the grains is aspired instead of a statistical distribution as for common electroplated layers, as applied in this study. Common segmented wheels also provide a statistical distribution, however, the reduction of abrasive layer is also far higher than for the segmented wheel used in this study (up to 40 % [9]). The low reduction of 8.5 % applied in this study was to examine the influence of the macro-topography on the cooling efficiency only, without influencing the chip removal mechanisms.

As a consequence, the machining heat for equal parameter combinations could be expected the same for the different wheels. However, the machining heat is also influenced by the friction. A higher amount of coolant in the contact zone not only promotes a higher cooling efficiency, but also a better lubrication (especially when grinding with oil). Thus, it can be expected that for the slotted grinding wheel less machining heat is generated in addition to a better heat dissipation.

Rising depths of cut at constant feed rates result into rising machining heat. This can be seen for the standard and the segmented grinding wheel. For the slotted grinding wheel, the superior cooling efficiency, in connection with the low feed rate (long process time), results into the dissipation of this heat. Rising feed rates result into higher intensity of the thermal load but at the same time a shorter duration of heat impact. For the segmented and the standard wheel, these shorter durations of heat impact entail lower depths of alterations of the surface integrity. As their cooling efficiency is low, a shorter process time (shorter duration of heat impact) promotes better surface integrity. For the slotted wheel it is vice versa. Because of its high cooling efficiency, longer process times, despite longer durations of heat impact, result into a better surface integrity. This can be led back to a longer time to dissipate the heat at high contact zone flow rates, and to the lower intensity of the thermal load.

4. Conclusion and Outlook

In this paper, three grinding wheels with different macro-topographies and their impact on the cooling efficiency and ultimately on the surface integrity of the ground workpieces was presented. Besides a standard electroplated grinding wheel with continuous abrasive layer, a segmented grinding wheel and a slotted grinding wheel were also evaluated. While the cavities of the segmented wheel were milled continuously from the centerline of the grinding wheel body to the edge of the body (segments), the cavities of the slotted wheel were limited to the workpiece width (slots). Thus, while the coolant transported through the segments can escape to the sides, the coolant transported through the slots is captured inside them and cannot escape.

The experimental investigations showed that the different macro-topographies resulted into completely different cooling efficiencies (exactly the same nozzles and nozzle parameters were applied for each grinding wheel). Also, the grinding wheels reacted different on the variation of the grinding parameters. However, for all parameters examined, the segmented grinding wheel resulted into the worst cooling efficiency and hence the biggest impact on the surface integrity, while the slotted grinding wheel showed the best cooling efficiency and ultimately the least impact on the surface integrity.

The slotted wheel revealed enormous potential to improve the cooling efficiency in grinding. Especially for low feed rates, where the two other wheels entailed the highest impact on the surface integrity. Thus, the slotted grinding wheels potential for creep feed mode has to be further investigated.

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