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The Use of the Size Effect in Grinding for Work-hardening

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Abstract
This paper shows the possibility of using the size effect of the specific grinding energy for a targeted surface layer work-hardening of metal parts. The research includes the combination of abrasive material removal and plastic deformation in a single grinding step. Therefore high specific energy values are needed and thermal effects counteracting the work-hardening have to be minimised. This can be achieved by low cutting speeds in combination with low depths of cut. The new approach results in an in-process work-hardening of the surface layer, which was found to lead to higher hardness, a compressive residual stress state, and higher wear resistance.

Keywords:
Grinding, Surface integrity, Residual stress

1 INTRODUCTION

In cutting and abrasive machining as well as in scratching the energy needed for the removal of a unit volume of material is used as an appropriate quantity to evaluate the process. This fundamental quantity, called the specific energy, shows a size effect [1], i.e., there is a pronounced increase at an exponential rate with smaller chip thickness [2, 3, 4]. This effect has been found in grinding metals as well as ceramics and has been attributed to chip formation with an increased ratio of micro-ploughing [5]. Material removal by micro-cutting does not occur before a certain threshold force is reached [6]. The required energy for chip formation is dominated by ploughing and depends more on the total area of the chips than on the chip thickness [7, 8]. Grinding with very small chip thickness values leads to a shift of the energy fractions. In this case the sum of the friction and plastic deformation energy fractions can exceed the pure cutting energy fraction [3]. For the characterisation of the prevailing grinding mechanisms the magnitude of the specific energy and its dependence on the operational conditions in grinding is required [9].

By generating large specific energies at very low removal rates with small grit depth of cut, a comparatively large plastic deformation energy fraction should be available. With this specific energy level the size effect can be used in grinding for work-hardening of the surface layer. However counteracting thermal effects must be held to a minimum. Due to low cutting speeds, maximum temperatures in the contact zone are estimated to be less than 300 °C [10]. Such low temperatures in addition to low material removal rates result in a new advanced grinding process which allows the combination of a shape-generating grinding process and a mechanical subsurface strengthening process in a single-step machining operation. In this paper the fundamental technological approach will be introduced by using a face grinding process. Based on these results, preliminary experiments with an industrial application in cylindrical grinding were performed. The evaluation of the achieved work-hardening was done by X-ray residual stress measurements, which can be used to assign the thermal or mechanical origin of the residual stresses [11].

2 FACE GRINDING

Fundamental experiments were conducted under face grinding conditions in the down mode on a machine tool designed especially for low cutting speeds (up to 10 m/s). Three grinding parameters – radial feed f_r, workpiece velocity v_w and wheel velocity v_s – were varied. The resulting speed ratio $q = v_s/v_w$ was held constant at $q = 2$ in all experiments. Measurements were made for grinding force components F_n and F_t by an integrated piezoelectric force dynamometer. As workpiece material, the heat treatable steel 42CrMo4 (AISI 4140) was used in the annealed state of approximately 300 HV 0.1 surface hardness. Cylindrical specimens were used (Ø 63 mm x 6 mm).

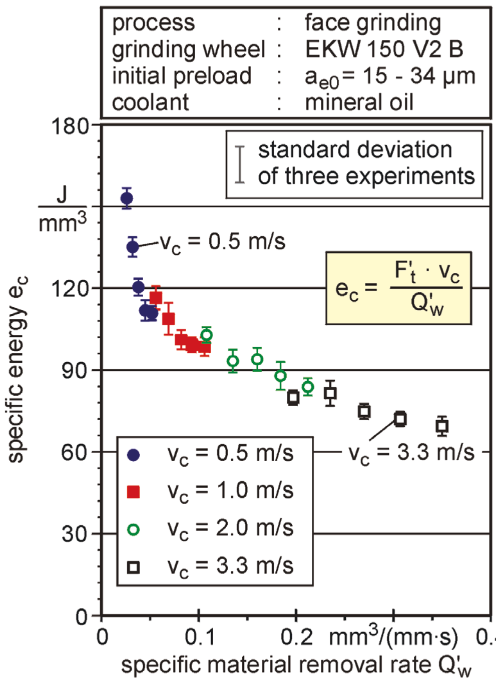

Figure 1: Specific grinding energy depending on the specific material removal rate.

The objective of the work was focussed on the effects for the specific energy of both the cutting speed and the depth of cut. The scope of the experimental investigation includes besides the grinding parameters also the influence of the grinding wheel specification with a variation of the bonding system and the grain size. Except for the grain size analysis all grinding operations were done with corundum wheels. To investigate the effect of the grain size on the specific energy, diamond abrasives were used in order to have no significant influence of abrasive wear during a single grinding cycle. The process analysis was made based on experimental data obtained from grinding tests. X-ray measurements of the workpiece residual stresses were carried out in order to characterise mechanically induced plastic deformations associated with the intended work-hardening effect. The ground workpieces were investigated on the surface and with a radial feed of $f_r = 0.04$ µm also depth profiles of residual stresses tangent to the grinding direction were determined by applying stepwise material removal by electrolytic etching. Each data point shown in the diagrams is the mean value of a series of three residual stress measurements. Standard deviation values of such series varied between approx. ± 10 and ± 30 MPa. Considering the results of all measurements, the measurement uncertainty is estimated to be less than ± 50 MPa. To enable a clearer comparison of the residual stresses, error bars of the single points are omitted.

2.1 Influence of the cutting speed

The specific energy was calculated from the ratio of the total grinding energy E and the effective material removal $V_{w,eff}$. The effective material removal $V_{w,eff}$ was calculated from geometrical conditions taking into account the workpiece width b_w as well as the actual workpiece diameter d_w before and the diameter decrease Δd_w after grinding. The total grinding energy is obtained from the product of F_t, v_c, and the machining time t_c. Figure 1 shows the calculated values of the specific grinding energy depending on specific material removal rate for four different cutting speeds. In all experiments with cutting speed variations the machining time t_c was matched to the peripheral work speed v_w, so that the number of wheel overruns and the nominal material removal $V_{w,nom}$ remained constant. When varying the cutting speed v_c, the radial feed f_r was maintained constant. The equivalent chip thickness h_{eq}, which is defined as the quotient of the specific material removal rate Q'_w and the cutting speed v_c, was constant as well due to the fact that the speed ratio is constant at q = 2. With these parameters the values of h_{eq} and f_r are equal. The radial feed f_r was varied in five steps from 0.04 µm up to 0.08 µm for every cutting speed. Each grinding experiment was repeated twice. As expected, the specific grinding energy e_c was found to increase with decreasing radial feed (equivalent chip thickness). At the same time, the cutting speed acts as an additional scaling factor influencing the specific grinding energy at a constant value of f_r (h_{eq}).

In Figure 2 the influence of the specific energy on the workpiece residual stresses in grinding direction is shown. Only compressive residual stresses in the range of -250 up to -400 MPa were measured on the workpiece surface throughout all the experiments which is in good agreement with previously reported results [12]. The compressive residual stress values increase with increasing specific energy indicating an effective suppression of thermal effects and a stronger workpiece surface plastic deformation in this direction. As already mentioned above, the specific energy increases (size effect) which, in turn, is related to micro-ploughing.

Increasing e_c resulted also in plastic deformations and thus strengthening of subsurface layers. Compressive residual stresses and micro-hardness (from 300 HV 0.1 up to 450 HV 0.1) increase were observed up to 30 µm depth.

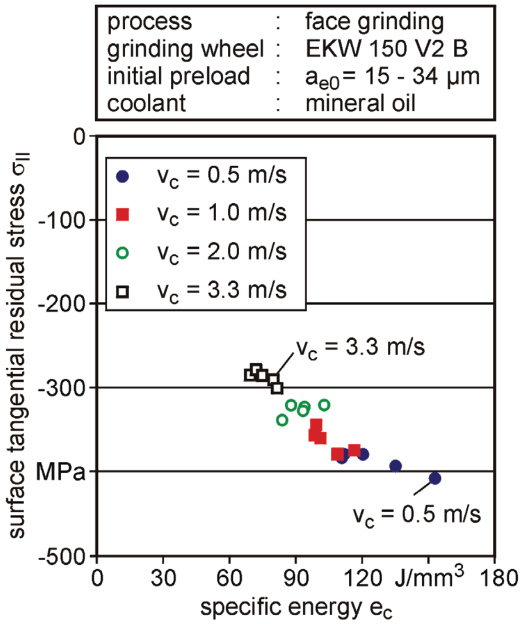

Figure 2: Tangential residual stress state of ground surfaces.

2.2 Influence of the abrasives grain size and the bonding system

The analysis of a grinding process with the specific energy is based on the total energy within the contact zone. Additional investigations to determine the influence of the grain size result in an important finding. When varying the diamond abrasive grain size the size effect was also observed including higher specific energy levels with a decreasing grain size. In contrast the measured values of compressive residual stress showed higher values on the surface and extended deeper into the subsurface, when the grain size is larger. Therefore single grain contact investigations were made by using the chip thickness model of Werner which assumes a non-uniform distribution of abrasive grains over the grinding wheel periphery and a triangular shape of the chip cross section [13]. The single grain specific energy e_g was estimated by relating the total specific energy e_c to the number of active grains predicted from the chip thickness model. With these calculations it could be shown that high compressive residual stresses are observed, if the specific energy per grain is high. This leads to the conclusion that the size effect for specific energy in grinding must be related to the single grain contact, if it is discussed in context with plastic deformation and mechanically induced compressive residual stresses.

The experimental investigations also included grinding tests using seven commercially available wheels with tool bonds belonging to different resin and vitrified systems. Besides the type of the matrix material, the systems were characterised by different relative pore volumes being comparatively high for vitrified bonds and low for resin bonds. Significant differences amongst the wheels investigated were observed. The results achieved have been analysed by means of a wear map and the above mentioned chip thickness model. With this analysis the differences could be related to different single grain forces, and more relevant, to changes in the chip formation. It was shown that greater micro-ploughing was observed when using resin wheels rather than vitrified ones.

A detailed description of these investigations is given in [14]. The results of the face grinding process can be summarised by the demand to generate high specific energy per grain with: low cutting speeds, low radial infeed, down-grinding, and a grinding wheel with large abrasive grains and an elastic resinoid bonding system.

3 EXPLOITATION OF FUNDAMENTAL RESULTS IN CYLINDRICAL GRINDING

To transfer the achievements from the fundamental research to an economic grinding process, higher cutting speeds have to be addressed. The process design must consider all requirements mentioned above, which lead to dominant mechanical effects within the contact zone. For this reason the transfer is aimed at fine grinding or finishing operations.

Preliminary tests to demonstrate the new approach were performed on the industrial application of grinding camshaft bearing surfaces. A three-step grinding cycle was used in an external cylindrical plunge grinding operation. For high quality bearing surfaces a surface roughness better than Rz ≤ 4 µm, a roundness limit of ± 4 µm, a deviation in cylindricity of maximum 7 µm, and a short grinding cycle time are required. The goal of a low speed finishing is not only to fulfil these tolerances but also to generate a mechanically induced strengthening of the surface layer. Tribological surfaces with an increased wear resistance and a high ratio of bearing contact area to total surface area have to be obtained.

The work was focussed on the comparison between the industrial application with a cutting speed of v_c = 60 m/s and a low speed alternative using v_c = 20 m/s. Besides the cutting speed all grinding parameters were kept constant (see Figure 3). As workpiece material, the low carbon steel S355J2G3 (St 52-3, 1.0570) was used. Cylindrical hollow shafts had an overall length of 200 mm, an outer diameter of 20 mm and a thickness of 3 mm. To ensure the repeatability of the results five bearing surfaces with a width of 20 mm were ground on a single shaft with constant parameters. Measurements were made of the grinding forces (Figure 3), the roughness (Figure 4), the roundness, and the cylindricity.

process	:	external plunge grinding
grinding wheel	:	A120 H8 V
workspeed	:	v_w = 0.6 m/s
total infeed	:	a_e = 0.2 mm
coolant	:	emulsion, 4 %
coolant flow rate	:	Q_{cl} = 20 l/min

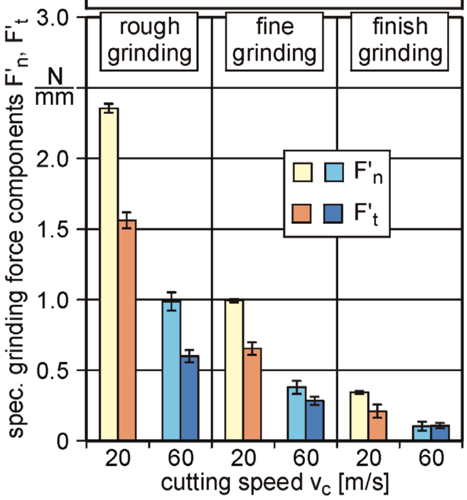

Figure 3: Specific grinding force components of a three-step grinding cycle for different cutting speeds.

A decrease of the cutting speed leads to an increase of the grinding force components. While higher loads occurred during grinding with v_c = 20 m/s the required quality was successfully realised with an average roundness value of 3.0 µm and a maximum difference of about 5.9 µm in cylindricity. In terms of surface roughness a slightly increased average value of Rz = 4.3 µm was observed. In addition the generation of higher grinding forces enables a higher potential for a mechanically induced strengthening of the surface layer.

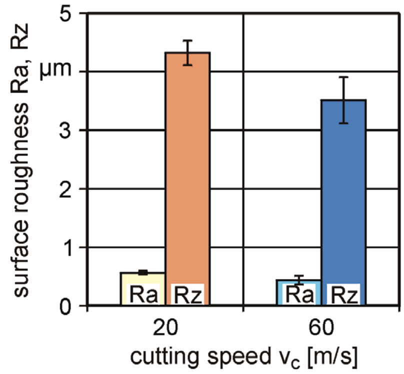

Figure 4: Roughness of the ground surface depending on the cutting speed.

The influence of the cutting speed on the workpiece residual stresses in grinding direction is shown in Figure 5. Before grinding a tensile stress of about 200 MPa was obtained on the surface of the drawn hollow shaft. With the conventional cutting speed only slight changes to compressive stresses were observed. The effected material layer has a maximum depth of 10 µm. Grinding with v_c = 20 m/s leads to two positive effects. Both the residual stress on the surface and the penetration depth were significantly increased.

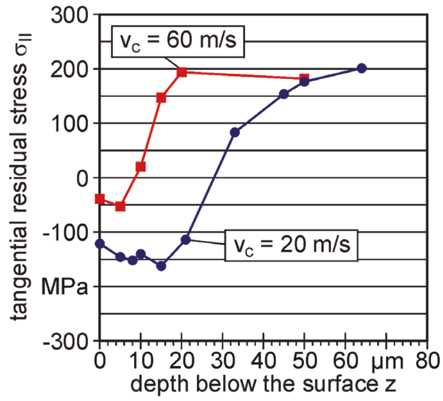

Figure 5: Depth profiles of residual stresses depending on the cutting speed using emulsion.

Wear resistance measurements were accomplished by ball-grinding (European Standard ENV 1072-2). A steel ball with a diameter of 20 mm lies between the ground surface and a rotating drive shaft. As the ball rotates, a 1 µm diamond slurry is dripped onto the ball, such that an elliptical wear pattern is ground into the surface layer. This procedure was repeated two times. The size of the cavities after 20 min is illustrated in Figure 6. The elliptical wear area observed was greater and deeper, when the surface was ground with the higher cutting speed. The presented wear area in Figure 6 (left) corresponds to a maximum depth of z = 10 µm which is comparable to the effected surface layer. In comparison, a cutting speed of v_c = 20 m/s leads to a decrease of the wear area of about 44 %, i.e., the maximum depth of the cavity was reduced to a depth of z = 6 µm. This decrease corresponds to the presented depth profile of residual stress. If the surface layer is predominantly mechanically effected by the grinding process, positive changes of the physical properties (residual stress, wear resistance) were achieved.

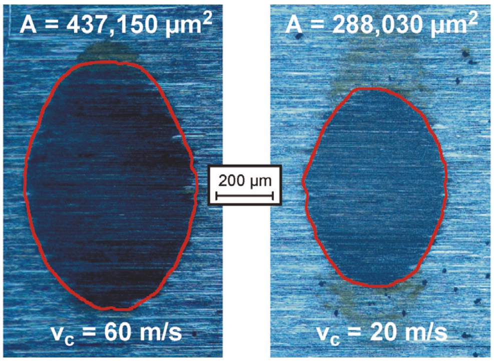

Figure 6: Wear analysis by ball cratering method.

The investigations confirm the work-hardening effects of the surface layer with lower cutting speeds. Due to micro-ploughing more plastic deformation occurs leading to an increased compressive residual stress state and a higher wear resistance.

In order to support the micro-ploughing effect more grinding experiments were done by using oil instead of emulsion as coolant. The results of the work-hardening are shown with the residual depth profiles in Figure 7. As a result of better lubrication of the grain material interaction with oil more micro-ploughing can be assumed. This leads for both cutting speeds to higher compressive residual stresses on the surface and in the case of v_c = 60 m/s also to a larger penetration depth than with emulsion as cooling lubricant.

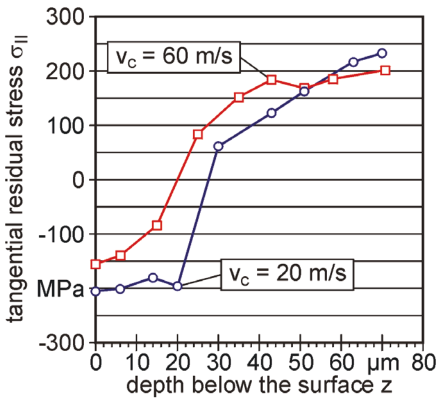

Figure 7: Depth profiles of residual stresses depending on the cutting speed using mineral oil.

Additional experiments were performed with an increased work speed. A reduction of cutting speed in down grinding was realised by an in-process increase of the number of workpiece revolutions during finish grinding and spark out, i.e., rough and fine grinding were carried out with conventional low revolution. A slight increase in the residual stress state was observed proving again the beneficial aspects of lower cutting speeds.

4 SUMMARY

An advanced grinding strategy was developed to utilise the size effect for specific energy in grinding for a targeted strengthening of the workpiece subsurface via work-hardening. It was found that the specific energy per grain was more important for the work-hardening rather than the total specific energy in the contact zone. To achieve high mechanical process effects and to minimise the thermal effects the grinding process requires a low cutting speed. Thus, if the chip thickness is constant, the chip formation mechanism shifts towards micro-ploughing and thus additionally increases the specific grinding energy.

The grinding strategy was successfully tested with an industrial process which demonstrated the potential of using the size effect of specific energy for an in-process work-hardening by grinding. Low cutting speeds in combination with low depths of cut resulted in negligible thermal effects and compressive workpiece residual stresses. Higher specific grinding energy values increased the absolute values of compressive residual stresses and their penetration depth. Wear analysis was presented which showed that a work-hardened surface layer increases the wear resistance. In future work, an attempt will be made to extend this new technology in grinding to more industrial applications with an increased work speed during fine grinding and sparking out. For the use of the size effect in grinding with dominant mechanical influence the authors suggest the term grind-strengthening.

5 ACKNOWLEDGMENTS

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