Characterization of the size effect and its influence on the workpiece residual stresses in grinding

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The paper deals with the quantification of the size effect in grinding and is aimed at demonstrating a possibility of using the size effect in grinding for a controlled subsurface work-hardening of metal parts. To achieve high specific energy values and to minimize thermal effects counteracting the work-hardening, the technological approach used implies application of low depths of cut in combination with low cutting speeds. Experimental results show a good correlation between specific grinding energy characterizing the size effect on the one hand and compressive residual stresses and their penetration depth characterizing the work-hardening on the other hand. To ensure a strong work-hardening, high specific grinding energy values resulting from the size effect can be utilized by a proper process design.

1 Introduction

In metal cutting and grinding operations it is well known, that energy needed to remove a unit material volume (specific energy) depends on the chip thickness [1-3]. With a smaller chip thickness the specific energy expenditure increases at a potential law due to an increased ratio of micro-plowing on chip formation. At the same time, the sum of the friction and plastic deformation energy fractions can exceed the pure cutting energy fraction when very small chip thickness values are applied [3], see **Fig. 1**.

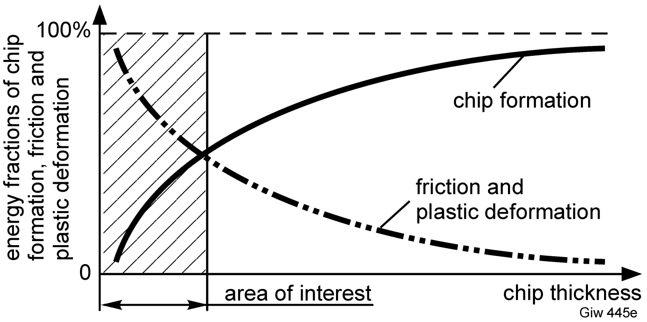

Fig. 1: Energy fractions in grinding dependent on the chip thickness [3]

If it would be possible to hold the frictionally induced heat amount at a low level, a comparatively large plastic deformation energy fraction should be available for work-hardening processes below the abrasive grain under these grinding conditions. The goal of this research project[*] is to utilize

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the size effect in grinding for a controlled work-hardening of the workpiece subsurface. By this, a new grinding technology should be developed allowing to combine a shape-generating grinding process and a mechanical subsurface strengthening process in a single machining operation. This paper shows the technological approach used and first results of experimental investigations.

2 Process design and experimental set-up

A strong work-hardening due to the size effect in grinding can be expected when the chip thickness is low and the prevailing chip formation mechanism is micro-plowing. An important prerequisite for the subsurface strengthening by a plastic deformation is, however, a low process temperature. To comply with these two requirements, the technological area of interest was restricted to low cutting speeds and low depths of cut, since latest investigations have shown, that choosing such grinding conditions both strong micro-plowing and low workpiece temperatures can be ensured [4]. Such process parameters are nowadays widely used for hard gear finishing in the technology called shave-grinding or gear honing.

Grinding investigations were performed in a face grinding process. The test bench used has been specially designed for grinding at low (up to 10 m/s) cutting speeds and allowed an in-process measurement of the grinding forces by an integrated piezoelectric force dynamometer [4, 5]. Process kinematics applied in the experimental investigations is shown in **Fig. 2**.

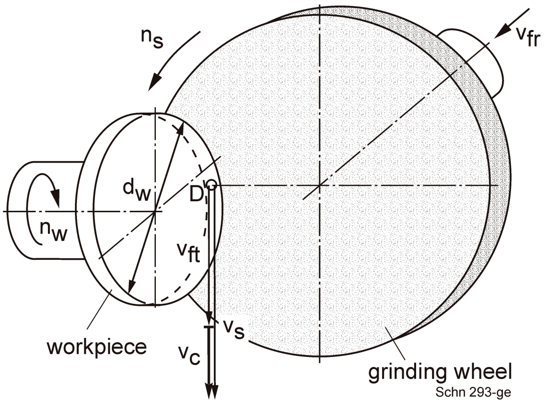
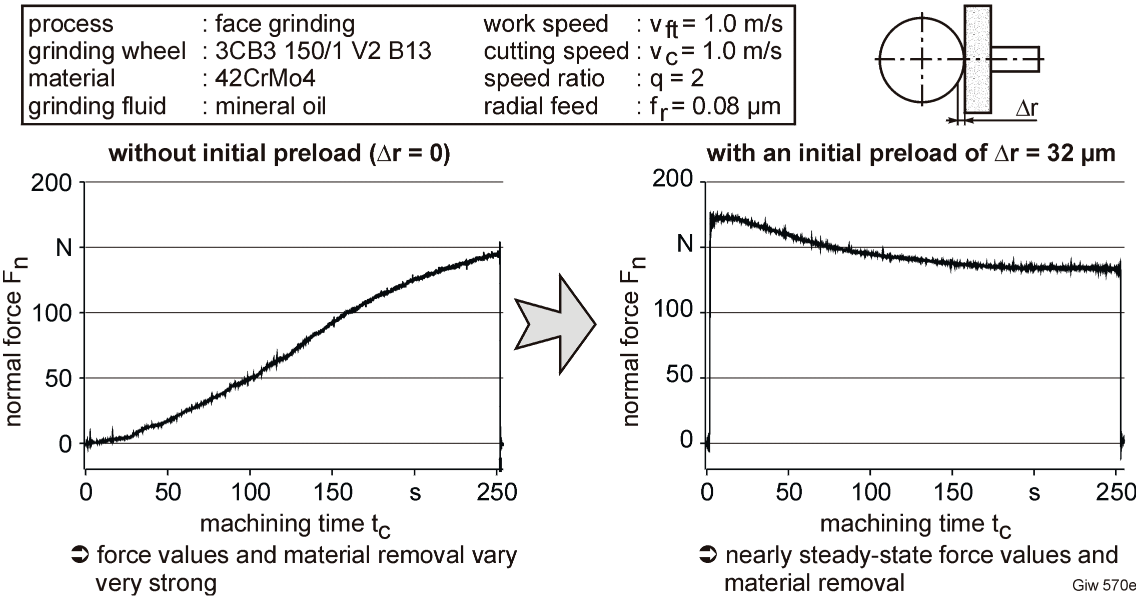


Fig. 2: Process kinematics in grinding experiments

Grinding wheel rotating at a speed v_s is plunged into workpiece rotating at a speed v_{ft} with a given working engagement f_r (radial feed per revolution). The cutting speed v_c is to a sufficient degree of accuracy the relative speed between the grinding wheel and workpiece peripheral speeds v_s and v_{ft} respectively, since the radial infeed speed v_{fr} is much lower than the both two.

As workpiece material, the heat treatable steel 42CrMo4 (SAE 4140) was used in the annealed state of approx. 300 HV 0.1 surface hardness. Cylindrical workpieces had an outer diameter of approx. 63 mm and a width of 6 mm. The grinding fluid used was a mineral oil. The grinding experiments were performed using a grinding wheel containing a mixture of conventional abrasive materials (seeded gel and white corundum) in a resin bond. The abrasives had grain sizes F180 and F150 (FEPA standard) corresponding to a mean grain diameter of 71 and 84 µm respectively.

Carrying out grinding experiments, radial feed f_r and cutting speed v_c have been systematically varied to quantify the size effect. In a good agreement with the state-of-the-art in grinding at low speeds, grinding forces showed to be dependent not only on the chosen f_r- and v_c-values, but also on the machining time t_c [5], see the left-hand side diagram in **Fig. 3**. As in such processes grinding force changes over the machining time correlate with changes of the effective material removal rate (e.g. rising forces correspond to increasing effective removal rates and vice versa [6]), chip formation is considered to be transient, when the grinding force course is unstable. To achieve a stable chip formation process over the machining time, it was found advantageous to maintain a steady-state course of the grinding force [7]. The steady-state course of the grinding force was achieved by introduction of an initial preload between tool and workpiece. The initial preload was realized as a quick motion of the tool towards the workpiece to a given depth Δr beyond the actual contact point. The initial preload was adjusted to the chosen radial feed providing a nearly steady-state time course of the grinding normal force, see the right-hand side diagram in **Fig. 3**. In order to precisely determine the contact point, an acoustic emission (AE) sensor was used for contact recognition. The AE-sensor was integrated in the grinding machine and connected to its CNC unit.



process	: face grinding	work speed	: v_{ft} = 1.0 m/s
grinding wheel	: 3CB3 150/1 V2 B13	cutting speed	: v_c = 1.0 m/s
material	: 42CrMo4	speed ratio	: q = 2
grinding fluid	: mineral oil	radial feed	: f_r = 0.08 µm

➲ force values and material removal vary very strong

➲ nearly steady-state force values and material removal

Fig. 3: Time courses of the normal grinding force component for different infeed strategies

The normal force experiences a jerk increase as soon as the initial preload is applied. Thereupon the grinding wheel is continuously fed into the workpiece and the level of the normal force is dependent mainly on the given amount of radial feed. The amount of initial preload needed to reach a nearly steady-state normal force course was ascertained empirically prior to the grinding experiment.

3 Results of the performed investigations

The size effect has been characterized by determining the specific grinding energy, which was calculated as the quotient of the total grinding energy E and the effective material removal $V_{w,eff}$:

$$e_c = \frac{E}{V_{w,eff}} = \frac{F_t \cdot v_c \cdot t_c}{V_{w,eff}} \qquad (1)$$

with machining time t_c and cutting speed v_c. Values of the tangential grinding force F_t were obtained from the in-process force measurement, 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:

$$V_{w,eff} = \frac{\pi}{2} \cdot \Delta d_w \cdot (d_w - \frac{\Delta d_w}{2}) \cdot b_w \tag{2}$$

Fig. 4 shows exemplarily the calculated values of the specific grinding energy depending on the radial feed for two different cutting speeds.

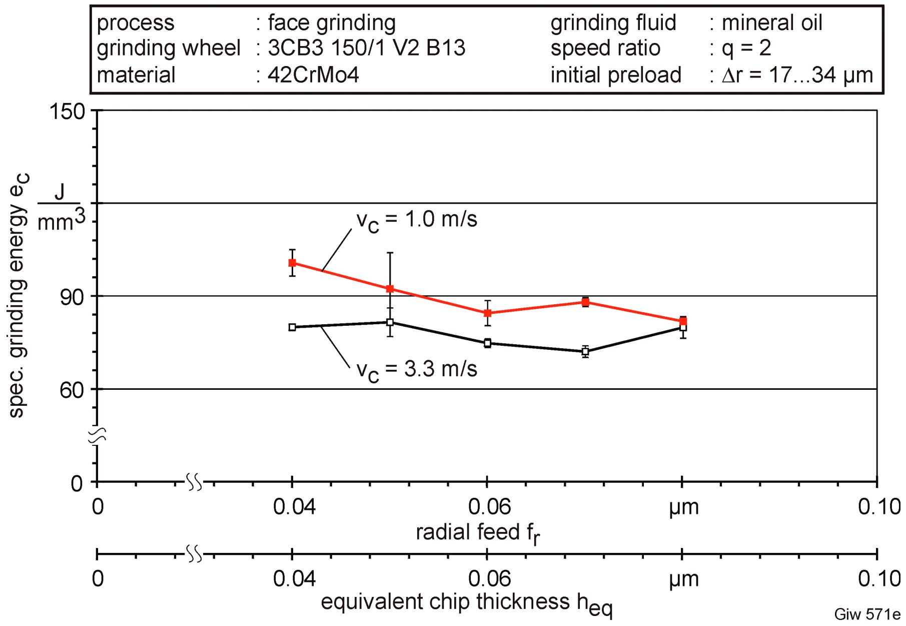


Fig. 4: Specific grinding energy dependent on the radial feed (equivalent chip thickness) for different cutting speeds

In all experiments, the speed ratio $q = v_s/v_{ft}$ was held constant at $q = 2$. When varying the cutting speed v_c, the radial feed f_r was maintained constant in the way, that the equivalent chip thickness h_{eq} was constant as well. The equivalent chip thickness, which is defined as the quotient of the specific material removal rate Q'_w and the cutting speed v_c, was regarded as an indirect measure for the real single grain chip thickness in grinding:

$$h_{eq} = \frac{Q'_w}{v_c} = \frac{v_{ft} \cdot f_r}{v_c} \tag{3}$$

Besides the equivalent chip thickness, in all experiments with cutting speed variations the machining time t_c was adjusted to the peripheral work speed v_{ft}, so that the number of wheel overruns and the nominal material removal $V_{w,nom}$ (see eq. (5)) remained unchanged. This strategy implied a proportional increase of machining time when decreasing cutting speed. Each grinding experiment has been repeated at least twice and deviations between the maximum, minimum and average e_c-values respectively are indicated by a scatter bar. As expected, specific grinding energy decreases continuously with increasing radial feed (equivalent chip thickness) due to the size effect. At the same time, cutting speed acts as an additional scaling factor influencing the specific grinding energy at a constant f_r- (h_{eq}-) value.

Similar results have already been reported for low speed grinding processes [4, 7] explaining the size effect by increasing micro-plowing, when both cutting speed and depth of cut are very low.

The authors propose to take the relative material removal V_{rel} with its extreme values $V_{rel} = 0$ for ideal micro-plowing and $V_{rel} = 1$ for ideal micro-cutting as a quantitative measure characterizing the efficiency of chip formation in grinding. The relative material removal V_{rel} is defined as the ratio of the effective material removal $V_{w,eff}$ to its nominal value $V_{w,nom}$:

$$V_{rel} = \frac{V_{w,eff}}{V_{w,nom}} \tag{4}$$

The effective material removal $V_{w,eff}$ is determined by eq. (2), whereas the nominal material removal $V_{w,nom}$ is assumed to be the sum of volumes removed as a result of initial preload $V_{w,preload}$ and continuous infeed $V_{w,cont}$:

$$V_{w,nom} = V_{w,preload} + V_{w,cont} = \pi \cdot \left[(d_w - \Delta r) \cdot \Delta r + (d_w - f_r \cdot n_w \cdot t_c) \cdot f_r \cdot n_w \cdot t_c \right] \cdot b_w \tag{5}$$

with number of workpiece revolutions n_w. Evaluating the results of grinding experiments shown above with respect to the relative material removal, a trend of increasing micro-plowing can be stated with decreasing radial feed (equivalent chip thickness), see **Fig. 5**. Again, lowering cutting speed at a constant f_r- (h_{eq}-) value additionally enhances micro-plowing.

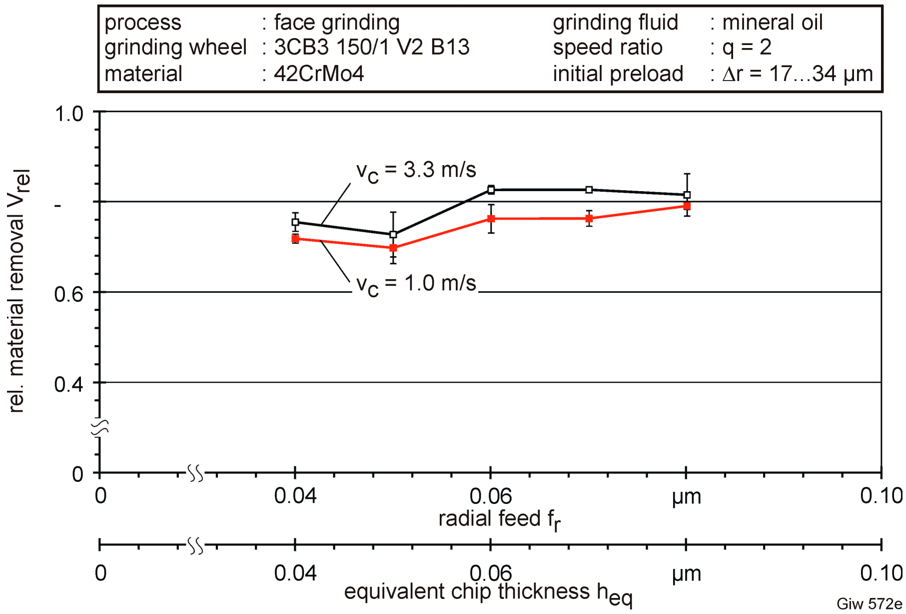


Fig. 5: Relative material removal dependent on the radial feed (equivalent chip thickness) for different cutting speeds

The size effect becomes more pronounced when viewing the average specific grinding energy per single grain $e_{c,g}$ instead of the total specific grinding energy e_c. The average specific grain energy $e_{c,g}$ was estimated by relating the total energy e_c to the number of active grains N_{act} accomplishing the actual chip formation in the contact zone. The number of active grains N_{act} was calculated by multiplying the dynamic grain number N_{dyn} with the contact zone dimensions width of cut a_p (equal to workpiece width b_w) and effective contact length l_e. The effective contact length l_e was computed according to Vansevenant [8] taking into account the mean peak-to-valley roughness parameter Rz, the radial feed f_r and the workpiece diameter d_w:

$$l_e = \sqrt{d_w \cdot (f_r + R_z)} + \sqrt{d_w \cdot R_z} \tag{6}$$

The dynamic grain number N_{dyn} was calculated according to Werner [9] as

$$N_{dyn} = 1{,}2 \cdot \left[\frac{2 \cdot C_1^2}{\tan\chi}\right]^{\frac{1}{3}} \cdot \left[\frac{1}{q}\right]^{\frac{1}{3}} \cdot \left[\frac{f_r}{d_w}\right]^{\frac{1}{6}} \tag{7}$$

with grain density C_1 and grain shape factor $\tan\chi$. The quantities C_1 and $\tan\chi$ describing grinding wheel topography have been determined by contact stylus roughness measurement of the wheel surface. For the tool used they amounted to $C_1 = 17360\ \text{mm}^{-3}$ and $\tan\chi = 5.63$. These topography data were furthermore used to calculate the maximum chip thickness $h_{cu,max}$ of a grain, which Werner [9] derived to be

$$h_{cu,\max} = 0{,}695 \cdot \left[\frac{2}{C_1 \cdot \tan\chi}\right]^{\frac{1}{3}} \cdot \left[\frac{1}{q}\right]^{\frac{1}{3}} \cdot \left[\frac{f_r}{d_w}\right]^{\frac{1}{6}} \tag{8}$$

Fig. 6 shows the calculated values of the average specific grain energy plotted against the radial feed (maximum chip thickness) for two different cutting speeds.

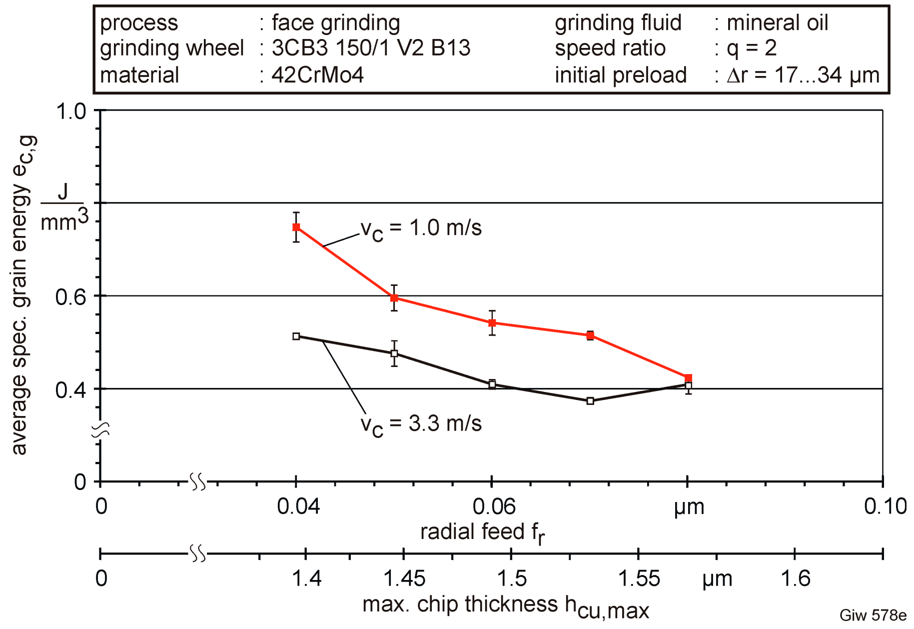


Fig. 6: Average specific grain energy dependent on the radial feed (maximum chip thickness) for different cutting speeds

As the maximum chip thickness was varied by means of the radial feed, a principle similarity in dependency of the specific grain energy on the both quantities is clearly evident. It is noteworthy, that absolute $h_{cu,max}$-values calculated according to the model [9] are virtually much greater than the radial feeds used – a situation, which is unlikely to occur in practice. This result shows low depths of cut to be an obvious limitation in applying Werner's model. The reason of this conflict is seen in the simplification of grain geometry with a taper cone, which is inappropriate for f_r-values much lower than the average cutting edge radius of a grain [4].

The influence of the specific grinding energy on the workpiece residual stresses along the grinding direction is shown in **Fig. 7**. The stresses were measured at the workpiece surface by an X-ray diffractometer using CrKα radiation.

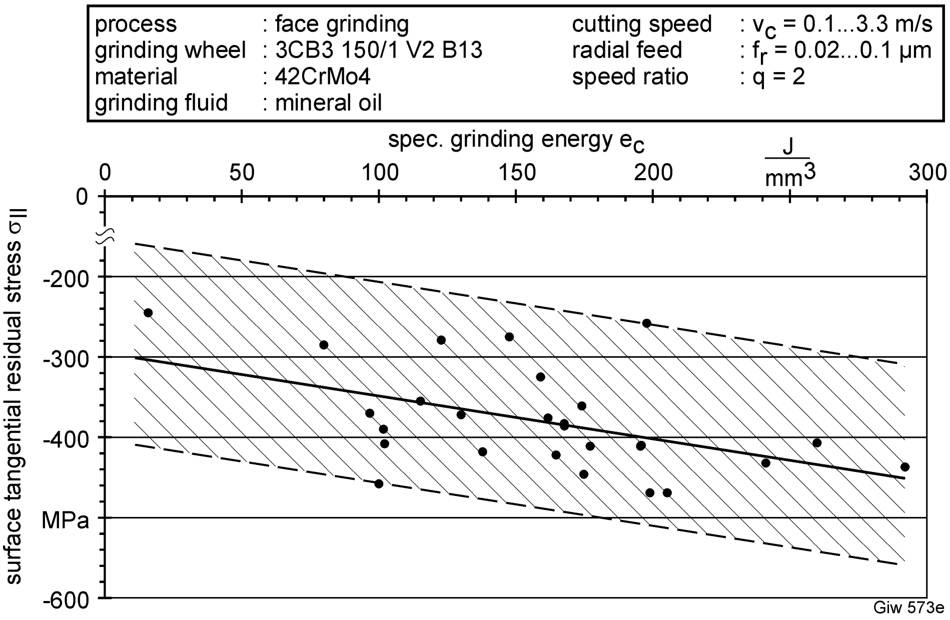


Fig. 7: Correlation between specific grinding energy and tangential residual stresses at the workpiece surface

Throughout all the experiments only compressive residual stresses of different amplitude were measured. The absolute stress values increase with increasing specific grinding energy indicating an effective suppression of thermal effects and a stronger workpiece surface deformation in this direction. As already mentioned above, specific grinding energy increases due to the size effect, which, in turn, is related to micro-plowing. Therefore, the result shown in **Fig. 7** originates from micro-plowing and the size effect as a consequence thereof.

An increase of plastic deformation with increasing specific grinding energy could be detected not only directly at the workpiece surface, but also in deeper subsurface layers. Depths profiles of residual stresses were measured applying stepwise material removal by electrolytical polishing. In **Fig. 8** residual stress depth profiles of two differently ground workpieces are exemplarily shown.

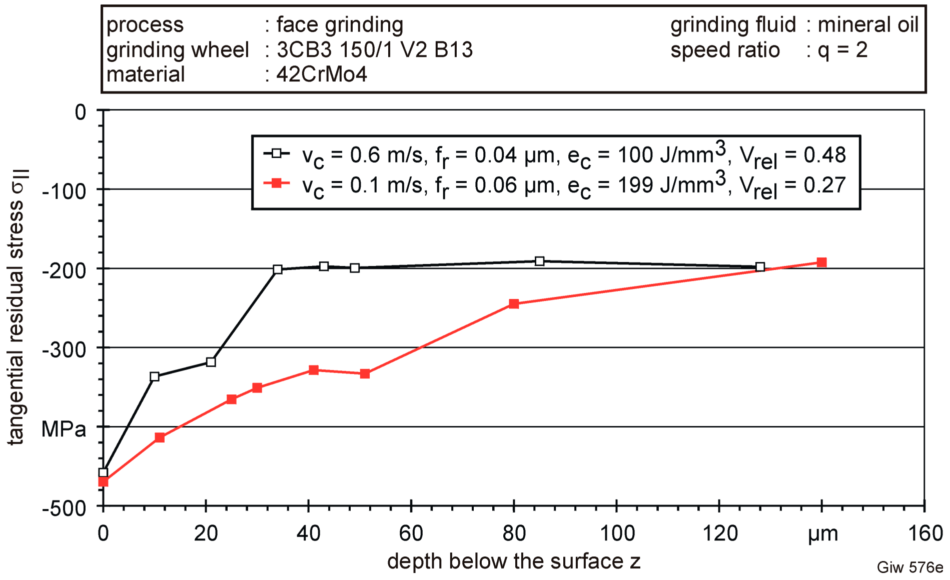


Fig. 8: Residual stress depth profiles of two differently ground workpieces

As can be seen, an increase of the specific grinding energy due to a stronger micro-plowing results in a significant increase of the penetration depth of compressive residual stresses and a smoother depth gradient of the stress. For the example observed, by a twofold energy increase the penetration depth was more than doubled. The maximum penetration depth accounted to approx. 80 µm, which essentially exceeds values of comparable grinding processes typically lying between 10 and 50 µm [10].

4 Conclusions

Investigations performed show a principle possibility of utilizing the size effect in grinding for a controlled strengthening of workpiece subsurface via work-hardening. Main physical quantity characterizing the size effect is specific grinding energy. Similar results were achieved with respect to the total specific energy and the average specific grain energy: both quantities increase with decreasing chip thickness. Lowering cutting speed at a constant chip thickness shifts the chip formation mechanism towards micro-plowing and thus additionally increases the specific grinding energy.

By application of low cutting speeds thermal effects were successfully suppressed and compressive workpiece residual stresses induced. Since higher specific grinding energy values were found to increase the absolute values of compressive residual stresses and their penetration depth, low cutting speeds and low depth of cut are considered to be promising for advanced investigations aimed at further development of this new technology.

5 References

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