A versatile method to determine thermal limits in grinding

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Abstract

This paper discusses a physical based method to determine limits with regard to the thermal impact of grinding processes on the machined workpiece surface layer. The thermal limits can be identified by analyzing the specific grinding power \( P^* \) and the contact time \( \Delta t \) between the grinding wheel and the workpiece. This approach will be exemplarily applied to grinding regimes during which intended phase transformations by grind-hardening and undesired grinding burn during shallow-cut grinding processes are generated. Theoretical analyses of Malkin’s burning limit show that it can also be expressed as a function between \( P^* \) and \( \Delta t \) on a double logarithmic scale. Moreover, an extension of Malkin’s burning limit is proposed in such a way that it can be applied to describe grind-hardening results in a physical based manner.

1. Introduction

During the manufacturing process of highly dynamically loaded parts, not only geometrical requirements, but also surface layer properties are to be respected due to their essential impact on the functional performance of the parts [1, 2, 3].

In order to fulfill the functional requirements of highly loaded parts, special attention is usually paid to the grinding process. Compressive residual stresses present a positive and tensile residual stresses a negative base load of the workpiece surface layer which is superimposed by external loads during the use phase of the part. Based on the thermal, mechanical and chemical impact on the machined surface, the grinding process has a major influence on the resultant properties of the machined surface including the subsurface layer. An excessive thermal impact, e.g. in the case of annealed steel workpieces, can cause an undesired hardness decrease and might lead to a negative influence on the functional behavior of the part.

The basic idea of the present research approach is to describe the thermal impact of grind-hardening processes on the workpiece surface layer with regard to Malkin’s burning limit.

2. Thermal impact of the grinding process on the workpiece surface layer properties

2.1. Malkin’s burning limit of the grinding process

A lot of scientific work has been devoted to explain the correlation of grinding parameters (e.g. cutting speed, feed speed, depth of cut) with the resulting surface layer properties. However, these correlations are mostly not sufficient to allow quantitative predictions over a wide range of grinding parameter combinations.

In order to describe the thermal impact of a conventional shallow-cut grinding process Malkin proposed a grinding burn criterion, which is based on Jaeger’s model of a two-dimensional plane band source of heat, moving along the surface of a semi-infinite solid.

Further considerations taking into account the following assumptions [4]
In order to avoid thermal damage of the workpiece surface layer, Malkin specifies a constant critical contact zone temperature $\theta^*$ depending on the workpiece material. It can be used to define a critical specific grinding energy $u^*$.

Replacing $q_w$ in equation (1) with $\varepsilon P_e$ and substituting $\varepsilon$ by the fraction of the energy partition to the workpiece $u - u_0$ and the specific grinding energy $u$, the grinding burn criterion can be written as a linear equation [4]:

$$u = u_0 + B \frac{d_e^2 \sigma_e^2 v_w}{k}\sqrt{\theta_m}$$

where $u_0$ can be approximated as 6.2 J·mm$^{-3}$ [4]. The constant $B$ is defined as $\frac{k \theta_m}{1.13 \sigma_e^2}$ and describes the slope of the specific grinding energy $u$ if it is plotted versus $d_e^2 \sigma_e^2 v_w^{-3}$. As a consequence a grinding burn free regime is separated from the occurrence of grinding burn by critical specific grinding energies into the workpiece $u^*$ lying on a straight line. If $u'$ exceeds the maximum allowable value $u^*$ a modification of process parameters is necessary.

2.2. Grind-hardening

As Brinksmeier and Brockhoff first showed in their investigations, in case of heat treatable steels an extensive heat generation can be utilized for short-time austenitization of workpiece surface layer. The subsequent self-quenching partially leads to a martensitic phase transformation of the surface layer. This technology is called grind-hardening [5, 6, 7].

Fundamental investigations were carried out to determine the basic mechanisms of short-time metallurgical processes, as well as the influence of the grinding parameters on the hardening result. It was shown, that grind-hardened parts are characterized by a fine-grained martensitic hardened layer up to a depth of 2 mm, as well as significant compressive residual stresses and improved wear resistance. It can be stated, that grind-hardening offers an alternative way to conventional surface layer hardening processes with a perspective of economic and ecological benefits [5].

As well as in the case of conventional heat treatment methods, the resulting structure of the workpiece surface layer primarily depends on the temperature development over the contact time $\Delta t$. This is affected by the workpiece material, the grinding wheel specification and the grinding parameters.

Extensive grind-hardening experiments were performed to analyze the influence of grinding parameters on the resulting workpiece surface layer properties. An investigation of the dependence of the resulting surface hardness on the depth of cut $a_e$ and the
workpiece speed \( v_w \) for various but constant material removal rates \( Q'_{w} \) is presented in fig. 1.

As seen in fig. 1, for specific material removal rates below a certain threshold value (here: \( Q'_{w} \leq 1.0 \) \( \text{mm}^3/(\text{mm.s}) \)) the energy flux into the workpiece is too low to austenitize the surface layer and grind-hardening cannot take place. When a critical specific material removal rate is reached (here: \( Q'_{w} \geq 3 \) \( \text{mm}^3/(\text{mm.s}) \)), the partially counteracting influences of the depth of cut \( a_c \) and the workpiece speed \( v_w \) on the resultant workpiece surface hardness have to be considered. Increasing the depth of cut leads to an increase in the specific grinding power \( P_c \). In order to keep the specific material removal rate constant, the workpiece speed \( v_w \) has to decrease proportionally to the increase of \( a_c \). This will lower the specific grinding power \( P_c \) but also leads to higher contact times, enabling a better heat diffusion from the contact zone into the workpiece material. Additionally chips will become thinner and a higher fraction of the specific grinding energy dissipates into the workpiece. As a result the grinding parameter regime for which grind-hardening occurs is different for different workpiece materials and grinding wheel specifications. However, the results in fig. 1 indicate that a lower boundary for the workpiece speed exists that prevents the onset of grind-hardening; for very low \( v_w \)-values the pronounced heat diffusion prevents quenching of the workpiece surface layer by the bulk material. Moreover, cooling conditions play an important role on heat partitioning in the contact zone [4].

As the actually known theoretical models and technical means cause great difficulties in determining the maximum contact zone temperature rise \( \theta_m \), or instead the specific grinding power \( P_c^* \) and the contact time \( \Delta t \) between one point of the machined surface and moving heat surface generated by the grinding wheel.

3. Analysis of grind-hardening results and their relation to Malkin’s burning limit for grinding processes

3.1. General research approach

The objective of this paper is to be characterized as a subgoal of long-term efforts within IWT, that are concentrated on developing diagrams, which should allow predicting the resultant workpiece surface layer properties as a consequence of the thermal impact during grinding process (e. g. occurrence of a rehardened layer, resulting residual stresses, surface hardness, surface hardening depth etc.). In this regard, fig. 2 shows schematically such kind of diagram for maximum contact zone temperature \( \theta_m \) versus contact time \( \Delta t \).

As the actually known theoretical models and technical means cause great difficulties in determining the maximum contact zone temperature rise \( \theta_m \), this paper offers a different approach to so far performed experiments, where instead of \( \theta_m \) the specific grinding power \( P_c^* \) as a function of the contact time \( \Delta t \) is observed. Consequently, an extension of Malkin’s burning limit on the grind-hardening results is possible. This approach should help to estimate the relationship between \( \theta_m \) and \( \Delta t \).

3.2. Procedure and results

Fig. 2. Schematic example of a \( \theta_m – \Delta t \) diagram.

After denoting Malkin’s experiments in the \( P_c^* – \Delta t \) diagram on a double logarithmic scale (fig. 3) it can be seen that there is a high probability of a linear relationship between both observed variables on a logarithmic scale. In order to support this statement, a further analysis based on Malkin’s expression of the burning limit criterion has to be performed. The heat flux \( q_m \) to the workpiece can be expressed as:
Combining the equations 1 and 3 leads to the logarithmic form of Malkin’s burning limit:

\[
\log \left( \frac{P_c}{W/mm^2} \right) + 0.5 \log \left( \frac{\Delta t}{s} \right) = \log K
\]

where \( K = \frac{\alpha_m}{1.13 \beta} \) and \( \beta = \sqrt{\frac{k \rho c_p}{s}} \).

Apart from Malkin’s experiments, results from extensive grind-hardening experiments (summarized in table 1) can be denoted in the same diagram, as seen in figure 3. The grind-hardening experiments based on various grinding operations using conventional corundum grinding wheels and various cooling conditions. The decisive criteria to separate positive and negative grind-hardening results are the achieved surface hardness (HRC) and the surface hardening depth \( s \). Compared to Malkin’s experiments, all positive grind-hardening results (HRC \( \geq 55, s \geq 0.5 \text{ mm} \)) were achieved by significantly higher contact times \( \Delta t \) (0.4 – 10 s).

Table 1. Summary of grind-hardening experiments and their marking in the figure 3.

| Experiment Nr. | Grinding process type           | Results and their marking | Malkin’s experiments |
|----------------|---------------------------------|---------------------------|---------------------|
| 1              | Surface grinding                | good                      | ▲ ▲ ▲               |
| 2              | Surface grinding, dry           | ■ ■ ■ ■ ■ ■               |                     |
| 3              | Surface grinding                | ■ ■ ■ ■ ■ ■               |                     |
| 4              | Surface grinding                | ■ ■ ■ ■ ■ ■               |                     |
| 5              | Surface grinding                | ■ ■ ■ ■ ■ ■               |                     |
| 6              | External cylindrical grinding   | ▲ ▲ ▲ ▲ ▲ ▲              |                     |
| 7              | Internal cylindrical grinding   | ▲ ▲ ▲ ▲ ▲ ▲              |                     |

It can be seen in fig. 3, it is possible to fit the positive grind-hardening results through a straight line. This suggests a connection to Malkin’s burning limit, as it was expressed by equation 4. However, a rather scattering of grind-hardening results is obvious. Moreover, slope of the linear fit of the grind-hardening results differs considerably from 0.5 (Malkin’s burning limit). These findings lead to the assumption that Malkin’s approach is not directly applicable to determine the onset of grind-hardening. Two factors are likely to be most important. First, the dependence between \( \theta_m \) and \( \Delta t \) in the case of grind-hardening has to be taken into account, which is supposed by earlier investigations of the grind-hardening process [4]. Second, the described effects can be a consequence of a varying energy partition to the workpiece \( \varepsilon P_c^* \). The \( \varepsilon \)-value may differ largely according to the actual grinding parameters and cooling conditions [7].

Based on the necessary prerequisite of a grind-hardening process, namely the austenitization of the workpiece surface layer, the dependence between \( \theta_m \) and \( \Delta t \) can be described according to time-temperature austenitization diagrams (TTA) [8]. Considering investigations concentrated on short-time metallurgical processes [9], the function \( \theta_m(\Delta t) \) can be approximated as:

\[
\theta_m = C_1 + C_2 \Delta t^{-C_3}
\]

where \( C_1, C_2, \text{ and } C_3 \) are non-negative real numbers. This approximation may be used for Malkin’s experiments as well as for grind-hardening results. To express Malkin’s burning limit taking into account equation 5, the constant \( C_1 \) would be the critical temperature \( \theta^* \) (approx. 780 °C [4]) and the constant \( C_2 \) would be equal to zero.

To express the function \( \theta_m(\Delta t) \) for grind-hardening experiments, the constant \( C_1 \) keeps the value of \( \theta^* \), which corresponds to a theoretical quasistatic austenitisation process (\( \Delta t \to \infty \)). The constants \( C_2 \) and \( C_3 \) have to be derived from resultant workpiece surface layer properties, e.g. the surface hardness or the surface hardening depth \( s \). To approximate \( C_2 \) and \( C_3 \), a simplified description of the temperature field along the contact length between workpiece and grinding wheel during grind-hardening is necessary.
The hardened part of the workpiece surface layer can be presented as a thin layer with a specific constant thickness \( s \). In order to simplify the complex transient heat flow conditions during the process (described by thermal simulations [10, 11, 12]), it is assumed that a maximum temperature rise \( \theta_m \) is present at the contact zone during the contact time \( \Delta t \). Assuming additionally that the bulk material temperature remains constant throughout the process, the temperature drop to austenitization temperature \( \theta^* \) should occur at a constant depth \( s \) (see fig. 4). Therefore the heat flow in the contact zone is constant and can be approximated by the linear heat transfer equation [13]:

\[
q_w = \varepsilon P_c = k \frac{\theta_m - \theta^*}{s}
\]  

This equation can be used to estimate the maximum contact zone temperature rise \( \theta_m \) by utilizing the specific grinding power \( P_c \), surface hardening depth \( s \) and specific grinding energy partition ratio \( \varepsilon \), which has to be estimated. This was done according to earlier studies of energy partitioning during grinding [5, 14, 15, 16].

Fig. 4. Heat flux through the workpiece surface layer.

In the case of the experiments 1 – 7 (denoted in the figure 3), \( \varepsilon \) was estimated taking into account the grinding parameters and cooling conditions as well. As the actual state of knowledge cannot provide universal formula to determine the value of \( \varepsilon \), various formulas were used, as seen in the table 2.

### Table 2. Formulas and values of \( \varepsilon \) for different grinding processes.

| Grinding process type          | Experiments | \( \varepsilon \) estimation | Method         |
|--------------------------------|-------------|------------------------------|----------------|
| Shallow-cut grinding           | 1, 3 - 7    | \( \varepsilon = 0.07 – 0.25 \) | calculated     |
| Creep-feed grinding            | 1, 3 - 7    | \( \varepsilon = 0.005 – 0.05 \) | calculated     |
| Dry grinding                   | 2           | Brockhoff [5], estimated     |                |
|                               |             | \( \varepsilon = 0.20 – 0.35 \) |                |

After estimating \( \varepsilon \), the grind-hardenning experiments were divided into three surface hardness classes (HRC 20 – 40, HRC 40 – 50, HRC 50 – 60). The \( \Delta t \)-values were directly calculated from the experimental conditions, the \( \theta_m \)-values were estimated according to equation 6. Obtained results are shown in the \( \theta_m – \Delta t \) diagram (figure 5).

For each of the hardness classes, a corresponding value of \( C_2 \) and \( C_3 \) from the equation 5 was approximated by the use of the least squares method.

**Fig. 5. Dependence between \( \theta_m \) and \( \Delta t \) for various hardness classes**

Both values of \( C_2 \) and \( C_3 \) are denoted in figure 6 for the mean values of HRC for each hardness class together with their 95% confidence intervals. In order to express the reliability of presented values \( C_2 \) and \( C_3 \), the limits of confidence intervals are drawn together with the curves \( \theta_m(\Delta t) \) as dashed lines in figure 5.

**Fig. 6. Values and confidence intervals of \( C_2 \) and \( C_3 \) for the defined hardness classes.**

Figure 6 shows that with increasing desired surface hardness, values of \( C_2 \) increase as well, while \( C_3 \) does not change strongly. That means, to reach a higher value of the surface hardness considering constant values of \( \Delta t \), the thermal impact of the grinding process has to ensure reaching a higher maximum contact zone temperature rise \( \theta_m \). This corresponds to the trend, which can be observed by the time-temperature austenitization diagrams. According to this trend, the temperatures needed to reach a positive hardening result increase with a decreasing value of \( \Delta t \). This can be explained by using the Avrami equation as a dependence between the newly transformed austenite rate and the contact time \( \Delta t \) [9]. Compared to the time-temperature austenitization diagrams used for longer times \( \Delta t \), corresponding to the
traditional heat treatment methods, the curves $\theta_m(\Delta t)$ are much steeper, which leads to higher temperatures, than it can be predicted by extrapolating the already known heat transformation diagrams towards smaller $\Delta t$-values. This finding corresponds to an earlier investigation of a short-time heating process [9].

The $\theta_m - \Delta t$ diagram shown in figure 5 can be used for multiple purposes, as it specifies a wider field of possible workpiece surface layer responses to the thermal impact during grinding process. While Malkin’s burning limit is denoted as a straight line of a constant temperature $\theta^*$, various values of the resultant surface hardness after grind-hardening are specified by estimating the constants $C_2$ and $C_3$ in equation 5. More exact estimations of the dependence $\theta_m(\Delta t)$ can be reached through detailed investigations of $\varepsilon$ for various grinding processes.

4. Conclusion

The described method of determining the dependence between the maximum contact zone temperature rise $\theta_m$ and the contact time $\Delta t$ offers a versatile method to predict the resulting thermal effect of the grinding process on the workpiece surface layer properties. It expands the Malkin’s burning limit by using the relations among process variables during grind-hardening, which were estimated by evaluating the results of extensive grind-hardening experiments. However, more exact approximations of $\varepsilon$ can improve the reliability of this estimation in the future.

To obtain a more exact description of the thermal impact during the grinding process, further experiments should be concentrated on measuring the process variables ($P^*_c$, $\theta_m$) for different values of grinding parameters under constant cooling conditions. By simultaneous evaluation of $P^*_c$, $\theta_m$, the workpiece surface hardness and the workpiece surface hardening depth it should be possible to improve the proposed approach by estimating the grinding energy partition ratio $\varepsilon$ with a higher reliability. Further, a comparison between measured values of $\theta_m$ and predicted values based on the proposed approach should be carried out to verify the primary assumptions about the temperature development in the workpiece surface layer.

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