Titel/Title: Surface layer modification charts for gear grinding

Autor*innen/Author(s): Stepan Jermolajeva, Ekkard Brinksmeier, Carsten Heinzel

Empfohlene Zitierung/Recommended citation:

Stepan Jermolajev, Ekkard Brinksmeier, Carsten Heinzel, Surface layer modification charts for gear grinding, CIRP Annals, Volume 67, Issue 1, 2018, Pages 333-336, ISSN 0007-8506, https://doi.org/10.1016/j.cirp.2018.04.071.

Verfügbar unter/Available at:
(wenn vorhanden, bitte den DOI angeben/please provide the DOI if available)

https://doi.org/10.1016/j.cirp.2018.04.071.

Zusätzliche Informationen/Additional information:

(https://www.sciencedirect.com/science/article/pii/S0007850618300957)

Abstract: In this paper, an approach to predict thermo-mechanically induced changes of sub-surface properties during discontinuous profile gear grinding is presented. The approach faces industrial boundary conditions, such as varying material stock removal as well as the drawback of possible localized thermal damage on the ground tooth flanks. The

Surface layer modification charts for gear grinding

Stepan Jermolajev[a,b], Ekkard Brinksmeier (1)[a,b], Carsten Heinzel (2)[a,b]

[a]*Leibniz Institute for Materials Engineering, Division Manufacturing Technologies, Badgasteiner Straße 3, 28359 Bremen, Germany*
[b]*University of Bremen, MAPEX Center for Materials and Processes, Bibliothekstraße 1, 28359 Bremen, Germany*

In this paper, an approach to predict thermo-mechanically induced changes of sub-surface properties during discontinuous profile gear grinding is presented. The approach faces industrial boundary conditions, such as varying material stock removal as well as the drawback of possible localized thermal damage on the ground tooth flanks. The basic idea is to consider the sub-surface properties after grinding as a function of "tempering time" and temperature due to the short-time heat treatment by the grinding process. Consequently, a time-temperature-diagram showing surface layer modifications for profile gear grinding based on the measurement of local contact zone temperatures has been set up.

Gear, Grinding, Thermal damage

1. Introduction, motivation and research objective

During profile gear grinding an elevated risk for thermal damage exists due to the line contact between grinding wheel and workpiece [1] as well as due to the typical artefacts resulting from the case hardening, such as thin (10 – 20 µm) surface oxidation layers with decreased hardness and increased ductility or localized very hard carbide networks. A further typical phenomenon contributing to thermal grinding damage results from varying material removal rates caused by the distortion of gear flanks due to the hardening process.

The identification of thermal process limits has been a research topic of utmost importance in the past [2, 3, 4].

From a physics point of view, the formation of surface layer properties is a function of temperature, duration time of heat impact as well as mechanical impact [5]. A simplified approach targeted for industrial boundary conditions was proposed by the authors in [6]. This approach is based on the premises of Carslaw and Jaeger [7] and maps the resulting surface layer properties over two selected parameters of the Carslaw-Jaeger-solution for contact zone temperatures: maximum contact zone temperatures T_{max} and contact times Δt (= l_g / v_{ft}) (in so called surface modification charts, Figure 1, right).

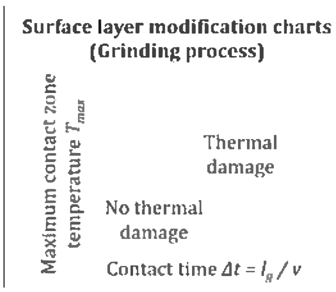

Figure 1. Sought time-temperature-diagram for discontinuou profile gear grinding.

However, the applicability of the surface modification charts for profile gear grinding has been unclear due to significantly different characteristics of profile gear grinding compared to surface grinding that was investigated in [6] (Figure 2). In particular, in profile gear grinding, the heat input varies due to both a varying local material stock removal Δs normal to the ground tooth flank and a varying specific material removal rate Q'_w along the ground tooth profile.

The complex process geometry of profile gear grinding also impedes the applicability of the so far conventional thermal approaches like for example [2] due to a limited validity of the Carslaw-Jaeger-approach [7]. As a result, the lack of industrially applicable approaches enforces multiple trial-and-error-tests leading to significant efforts and costs.

Therefore, the target of this paper is to examine the applicability of surface layer modification charts for profile gear grinding. Moreover, the demand for practical applicability requires to consider that the actual depths of cut a_e, and thus the contact times Δt (= l_g / v_{fa}) are unknown due to geometrical deviations of the gears resulting from previous production steps.

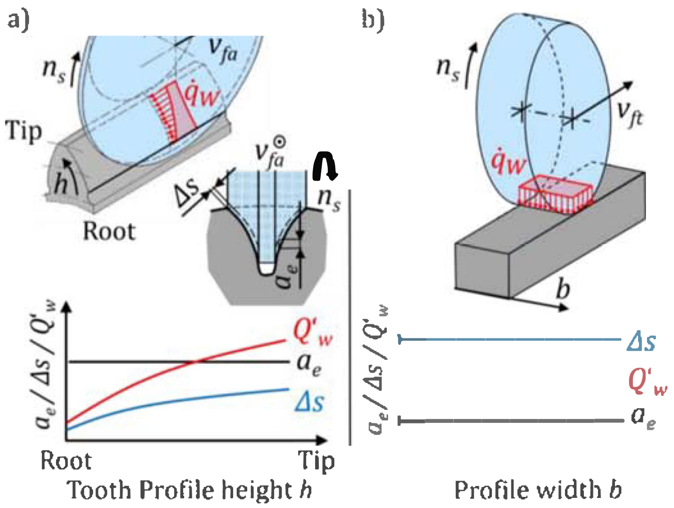

Figure 2. Analysis of local depth of cut a_e, material stock removal Δs and specific material removal rate Q'_w for a) discontinuous profile gear grinding after [1] and b) surface grinding.

The typical results of varying contact conditions during profile gear grinding are inhomogeneous surface layer properties of the ground tooth flanks (Figure 3).

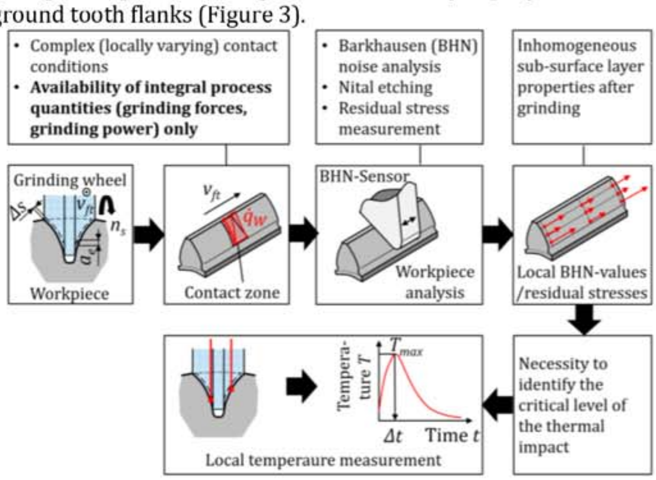

Figure 3. Introduction of the analysis chain.

Thus, the resulting surface layer properties can be identified precisely only by post-process-analysis, such as Barkhausen noise measurement or residual stress measurement at multiple surface spots of a gear flank. An in-process-detection of thermal damage under industrial boundary conditions is not possible so far, since the available signals (grinding power, AE-signal etc.) result from the sum of all local contact conditions on both ground tooth flanks. Consequently, there is a very low chance to detect strictly localized thermal damage, which is a quite frequent phenomenon during gear grinding processes.

In this paper, the in-process-detection of local thermal damage is aimed at by using an infrared temperature measurement system, which was presented in [6], in combination with a newly developed surface layer modification chart adapted to the specific characteristics of gear profile grinding. Due to the complex geometric conditions during gear profile grinding, it is at least questionable, if it is still an appropriate assumption, that a heat impact on one specific spot of the ground surface at the tooth flank can be estimated with Δt calculated from the local geometric contact length l_g and the axial feed speed v_{fa}. Therefore, in a first step, this issue has to be analyzed. In the case of insufficient results, a new approach to estimate the heat impact duration is needed and has to be elaborated in a second step. The main research hypothesis of this paper is that the critical temperature and heat impact duration depend on the preceding heat treatment, the gear was exposed to before profile grinding takes place. In conventional heat treatment, the well-known Hollomon-Jaffe-parameter [8] is an appropriate quantity to characterize thermal effects taking temperature and time into consideration. In the following, both quantities will be considered based on experimental and analytical investigations.

2. Experimental and analytical procedure

In order to set up surface modification charts for profile gear grinding, two different process strategies were chosen: a) the material stock removal was equalized by a damage-free pre-grinding process (the grinding parameters are listed in Figure 4). Thus, a defined material stock removal Δs and defined contact times Δt during the subsequent grinding experiments were assumed. b) A surface modification chart was sought for non-pre-ground gears with common concentricity deviations (up to 100 µm) as well as with previously described surface oxidation layers. Especially the non-defined material stock removal Δs requires a reasonable extension of the basic approach according to [6] to set up surface modification charts, since the contact times Δt cannot be identified in advance.

All grinding experiments were performed by keeping the nominal depth of cut a_e constant over the whole ground tooth profile. The contact zone temperatures were measured at two locations: 1) T_1 at the left flank near the tooth root and 2) T_2 at the right flank near the pitch circle. Based on its temperature stability and emissivity, which is comparable to steel surfaces, a platinum heating element was used to calibrate the infrared temperature measurement system. The measured temperatures are thus assumed to be a good approximation of the real contact zone temperatures.

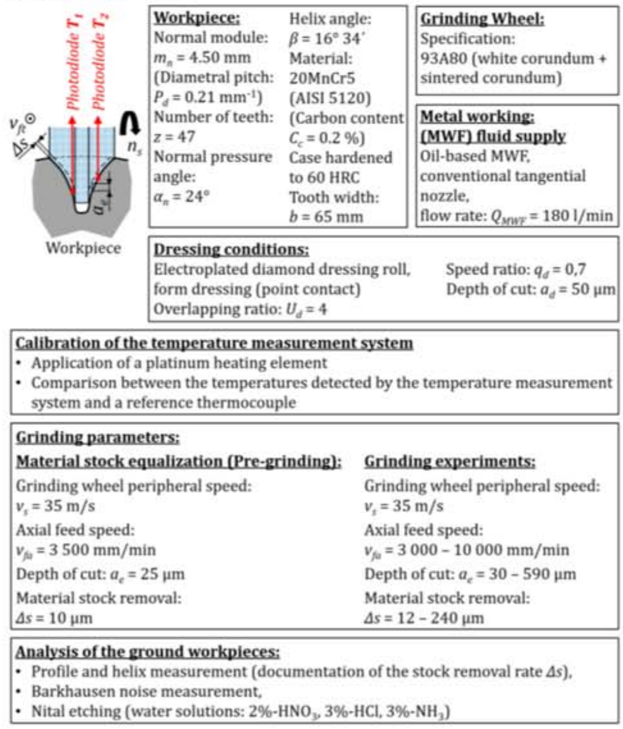

Figure 4. Experimental setup and workpiece analysis.

The analysis of the ground workpieces included an identification of the material stock removal Δs by a profile and helix measurement before and after grinding as well as the combination of Barkhausen noise measurement and nital etching to detect thermally damaged areas on the ground flanks. The resulting surface layer properties at the locations T_1 and T_2 along the ground tooth profiles were consequently linked to the locally measured temperatures during the grinding process and presented as single points in the targeted surface modification chart. The values of the contact time Δt were calculated by using the following equation:

$$\Delta t = \frac{l_g}{v_{fa}} = \frac{\sqrt{a_e \cdot d_y}}{v_{fa}}, \tag{1}$$

where d_y denotes the local grinding wheel diameter at T_1 and at T_2 respectively.

3. Results and discussion

After pre-grinding, two areas of surface layer properties were identified in the resulting surface layer modification chart (Figure 5). Ground tooth flanks with no thermal damage are characterized by relatively low levels of Barkhausen noise and metallographic cross sections indicating no undesired changes of the initial surface layer state. In contrast to that, thermally damaged tooth flanks can be characterized by significant changes of the Barkhausen noise level in combination with dark etching areas resulting from the nital etching procedure and the subsequent metallographic inspection. The primary focus was laid on the industrially relevant transition between no thermal damage and dark etching areas which are frequently the primary subject of industrial grinding burn tests [4]. However, especially at lower contact times Δt (marked area in Figure 5), this transition could not be identified clearly. This limits the applicability of the presented surface modification chart in a certain but relevant region.

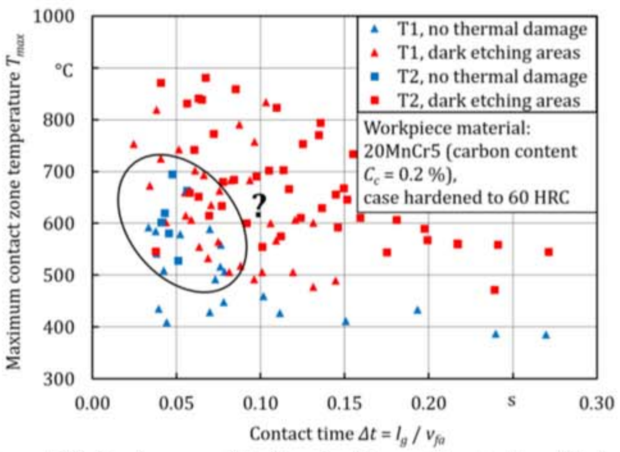

Figure 5. Surface layer modification chart for profile grinding of the tooth root (referring to the position of the optical fiber T_1) and the pitch diameter (T_2) after pre-grinding (constant material stock removal Δs).

The unclear transition between the area of no thermal damage and the area of thermal damage is assumed to be caused by the simplified calculation of the contact time Δt according to Equation (1). The time during which a single point of the workpiece surface experiences increased contact zone temperatures may differ from the value of Δt. This can be seen in Figure 6a, which depicts exemplary time-temperature-plots (calculated according to Carslaw and Jaeger) at a single point of the workpiece surface. It is clear, that the heat impact duration, quantified by the tempering time Δt_t over the tempering temperature T_t, can significantly exceed the contact time Δt, which is reached approximately at the maximum contact zone temperature T_{max}. In Figure 5, this phenomenon was neglected, which led to a partial overlap of the considered areas of surface layer properties without a clear transition line.

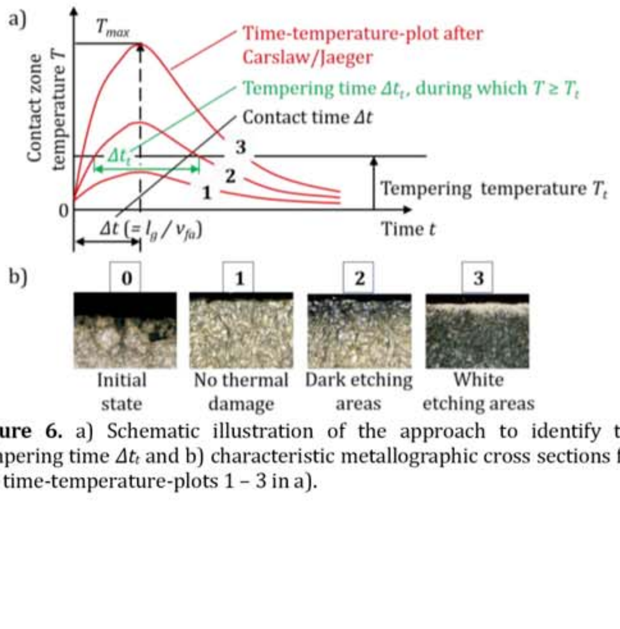

Figure 6. a) Schematic illustration of the approach to identify the tempering time Δt_t and b) characteristic metallographic cross sections for the time-temperature-plots 1 – 3 in a).

According to [8] in conventional heat treatment, thermally induced changes of the workpiece material properties can be characterized by temperatures exceeding the tempering temperature T_t achieved during the preceding heat treatment. This explanation can be considered as being valid in the case of short contact times since temperatures below the tempering temperature T_t would require significantly longer contact times (beyond the common contact time range for grinding processes) to cause a detectable change of the surface layer properties.

However, in grinding, exceeding the tempering temperature T_t does not necessarily imply thermally induced changes of the workpiece surface layer, as the results in Figure 5 show. Thus, it is assumed that a time-based criterion is needed in addition. Since the physics background of thermal damage are identical in conventional heat treatment and in grinding [8], it is reasonable to introduce an analogy to the empirical Hollomon-Jaffe-Parameter H from the conventional heat treatment for the profile grinding process considered in this paper:

$$H = \frac{\frac{T}{[K]} \cdot \left(C + \log\frac{t}{[h]}\right)}{1000}, \tag{2}$$

where the material constant C has to be estimated experimentally. The Hollomon-Jaffe-parameter H quantifies the change of workpiece material properties after tempering as a function of time t and temperature T. Thus, the "degree" of thermal impact during grinding can be correlated with a change of the H-value. Deductively, it is reasonable to assume, that the thermal damage limit during the grinding process can be identified by setting the Hollomon-Jaffe-parameter H to a critical value H_c. Considering the non isothermal impact during grinding and according to the recommendations summarized in [9], temperature T can be approximated by the "peak" temperature T_{max} and time t by the tempering time Δt_t:

$$T_{max} = \frac{1000 \cdot H_c}{C + \log \Delta t_t} \tag{3}$$

If the surface modification chart is modified by substituting the contact time Δt by the tempering time Δt_t, a clear transition line corresponding to the onset of dark etching areas is visible (Figure 7). Since only the maximum contact zone temperatures T_{max} were experimentally measured, the tempering times Δt_t were estimated from time-temperature-plots according to the Carslaw-Jaeger-solution for known values of l_g and T_{max}. This has to be considered as a first approximation of the real tempering times Δt_t, since the validity of assumptions of Carslaw and Jaeger is limited.

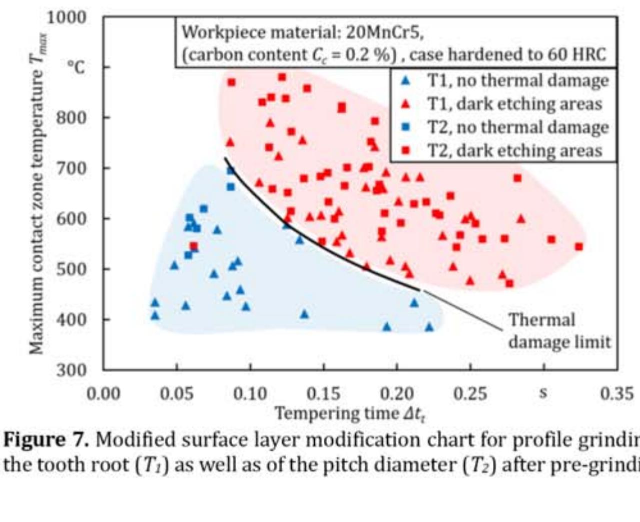

Figure 7. Modified surface layer modification chart for profile grinding of the tooth root (T_1) as well as of the pitch diameter (T_2) after pre-grinding.

The tempering temperature T_t used to calculate the Δt_t-values matches the preceding heat treatment (200 °C).

However, the transition line representing the onset of first dark etching areas can be identified well by assuming H_c = const. and approximating T_{max} according to Equation (3). Finally, the thermal damage limit can be approximated by the following function resulting from Equation (3):

$$T_{max} \cong \frac{1300 \pm 20}{(6.00 \pm 0.05) + \log \frac{\Delta t_t}{[h]}} \cdot [K]; \qquad C = (6.00 \pm 0.05); \quad H_c = (1.30 \pm 0.02); \qquad (4)$$

which is valid for the interval of tempering times Δt_t = 0.08 – 0.22 s. The approximated value of C differs significantly from its common values in conventional heat treatment (C = 15 – 23 for various workpiece materials, as reported in [9]). It is questionable, if this difference is caused by a possible deviation between measured and real contact zone temperatures T_{max}. However, by assuming $C > 15$ in Equation (3), the effect of varying tempering times Δt_t on the critical T_{max}-value would be almost insignificant, which contradicts the experimental observations. Thus, it can be assumed, that the grinding process (due to its short-time non isothermal impact) requires C-values, which cannot be predicted on the basis of conventional heat treatment processes.

As depicted in Figure 7, the thermal damage limit given by Equation (4) works well for both locations at the tooth root (T_1) and at the pitch diameter (T_2). This indicates a significantly improved applicability of the modified surface modification chart in Fig. 7 for multiple different locations along the ground tooth profile.

In the case of non-pre-ground gears, the exact calculation of the contact times Δt is not possible due to varying material stock removal rates Δs. Thus, similarly to the analytical procedure for pre-ground gears, tempering times Δt_t need to be estimated by means of the Carslaw-Jaeger-solution for contact zone temperatures.

Due to the surface oxidation layer of non-pre-ground tooth flanks, it is expected that the thermal damage limit for non-pre-ground gears will deviate from its approximation after pre-grinding in Equation (4). This can be seen in the resulting surface modification chart for non-pre-ground gears in Figure 8.

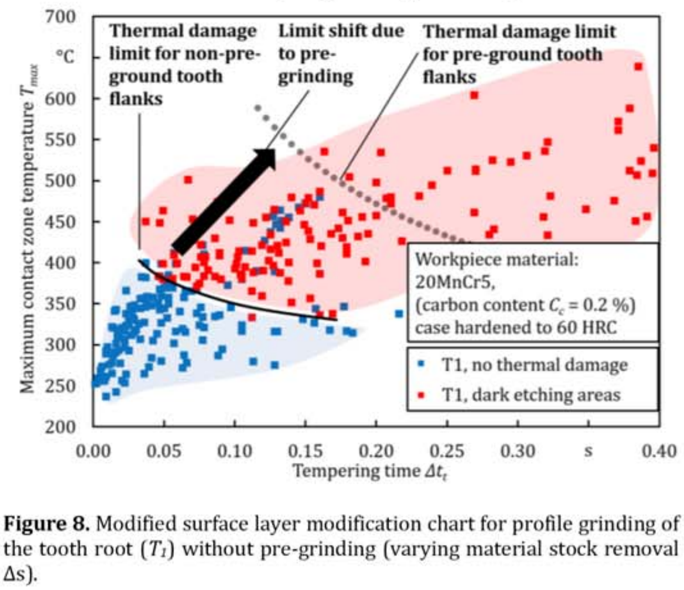

Figure 8. Modified surface layer modification chart for profile grinding of the tooth root (T_1) without pre-grinding (varying material stock removal Δs).

The thermal damage limit for non-pre-ground workpieces can be described by the following function:

$$T_{max} \cong \frac{4000 \pm 50}{(11.00 \pm 0.1) + \log \frac{\Delta t_t}{[h]}} \cdot [K]; \qquad C = (11.00 \pm 0.10); \quad H_c = (4.00 \pm 0.05); \qquad (5)$$

which is valid for Δt_t = 0.12 – 0.30 s. The approximation of the thermal damage limit for non-pre-ground gears provides, if compared with the results for pre-ground gears, different values of C and H_c. This is most probably due to different workpiece material properties within as well as directly beneath the surface oxidation layer, which consequently leads to an altered surface modification chart. It seems that the presence of the surface oxidation layer, which reveals approximately the hardness of an unhardened steel, causes the "decrease" of the thermal damage limit indicated in Figure 8. Nevertheless, the results obtained here clearly confirm the significant impact of the surface oxidation layer observed in industrial practice with regard to a higher risk of thermal grinding damage.

4. Conclusions and outlook

The results show that the application of surface layer modification charts for discontinuous profile gear grinding requires a substitution of the contact times Δt resulting from the geometrical contact length l_g and the axial feed speed v_{fa} by tempering times Δt_t. The tempering times Δt_t provide a more precise quantification of the time-dependent thermal impact and allow a clearer definition of thermal limits during the grinding process. These are identified by setting up an analogy of the Hollomon-Jaffe-parameter H originating from the conventional heat treatment. In the case of pre-ground gears it was shown that the identified thermal limit by means of a critical Hollomon-Jaffe-parameter H_c works well at different locations along the ground tooth profile.

Future research activities will include the identification of thermal limits for different typical gear materials and heat treatment states. Moreover, the approach presented in this paper shall be used to optimize multistage processes by elaborating a critical heat affected depth after roughing to be removed by a subsequent finishing.

5. Acknowledgements

The authors of this paper would like to thank the Deutsche Forschungsgemeinschaft (DFG) for funding the project HE 3276/6-3.

References

[1] Karpuschewski, B., Knoche, H. J., Hipke, M., 2008, Gear finishing by abrasive processes, CIRP Annals, 57/2:621-640.
[2] Rowe, W. B., Morgan, M. N., Black S. C. E., Mills, B., 1996, A Simplified Approach to Control of Thermal Damage in Grinding, CIRP Annals, 45/1:299-302.
[3] Brinksmeier, E., Aurich, J. C., Govekar, E., Heinzel, C., Hoffmeister, H. W., Klocke, F., Peters, J., Rentsch, R., Stephenson, D. J., Uhlmann, E., Weinert, K., Wittmann, M., 2006, Advances in Modeling and Simulation of Grinding Processes, CIRP Annals, 55/2:667-696.
[4] Malkin, S., Guo, C., 2007, Thermal Analysis of Grinding, CIRP Annals, 56/2:760-782.
[5] Brinksmeier, E., Klocke, F., Lucca, D. A., Sölter, J., Meyer, D., 2014, Process Signatures – A New Approach to Solve the Inverse Surface Integrity Problem in Machining Processes, Procedia CIRP, 13:429-434.
[6] Jermolajev, S., Epp, J., Heinzel, C., Brinksmeier, E., 2016, Material Modifications Caused by Thermal and Mechanical Load During Grinding, Procedia CIRP, 45:43-46.
[7] Carslaw, H. S., Jaeger, J. C., 1946, Conduction of Heat in Solids, First Edition, Oxford University Press, New York.
[8] Jaffe, L. D., Swartz, B., 1944, Time-Temperature relations in tempering steel, Experimental report, Issue Number 198122, Watertown Arsenal Labs.
[9] Canale, L. C. F., Yao, X., Gu, J., Totten, G., 2008, A historical overview of steel tempering parameters, International Journal of Microstructure and Materials Properties, 3:474-525.