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Surface layer modification charts for gear grinding

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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 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.

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 [2–4].

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 Ref. [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, Fig. 1, right).

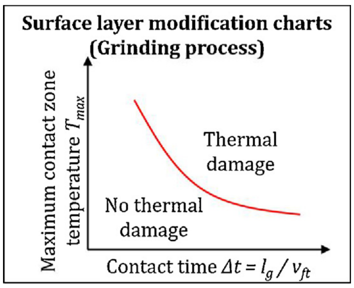

Fig. 1. Sought time–temperature-diagram for discontinuous profile gear grinding.

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 Ref. [6] (Fig. 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

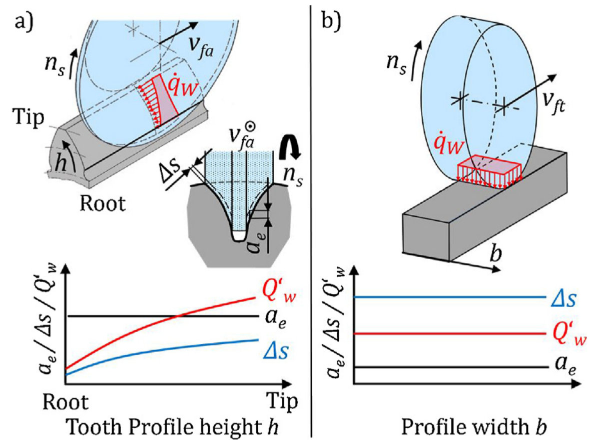

Fig. 2. Analysis of local depth of cut a_e, material stock removal Δs and specific material removal rate Q'_w for a) discontinuous profile gear grinding after [1] and b) surface grinding.

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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.

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

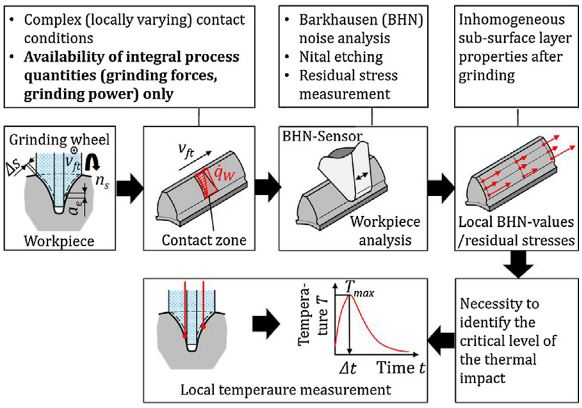

Fig. 3. Introduction of the analysis chain.

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 Ref. [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 newapproach 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 Fig. 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 Ref. [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.

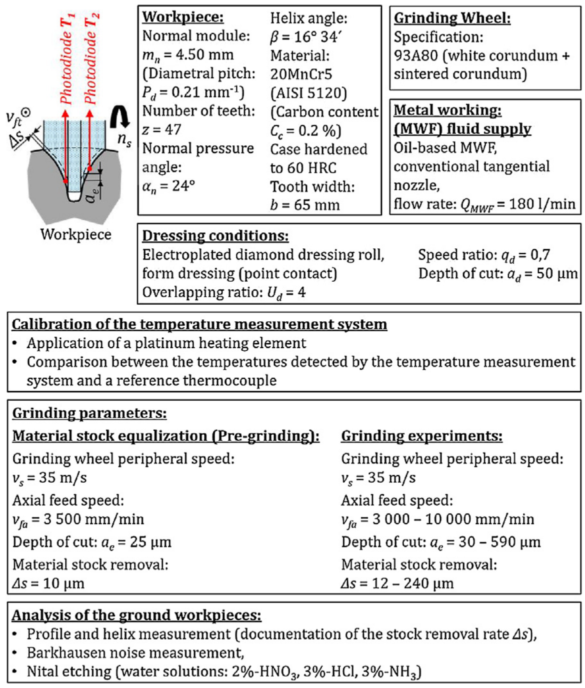

Fig. 4. Experimental setup and workpiece analysis.

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:

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

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 (Fig. 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