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# Discontinuous profile grinding of multi-phase, case-hardened gears with improved load-carrying capacity

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ABSTRACT

Highly-loaded transmission components like gears are case hardened for most applications to reach a load adapted strength. The surface layer microstructure as a function of heat treatment decisively determines the achievable load-bearing properties of the component as well as the technological limits of gear grinding. Against this background, this paper deals with the machinability (discontinuous profile grinding) of differently (carburizing and carbonitriding) case-hardened gears with various multi-phase microstructures and improved load-carrying capacity. Therefore, effects of different material phases, precipitates and their distribution in the surface layer on the gear-grinding process will be discussed.

## 1. Introduction, motivation and research objective

In order to achieve the highest possible resource efficiency, increasingly demanding requirements are being placed on the strength properties and the resulting service lives of dynamically highly-loaded components such as shafts, pistons, bearings and gears. A great potential to meet these increasing requirements can be seen in the use of innovative heat-treatment processes. At present, those components are usually heat treated by case hardening with gas or low-pressure carburizing in combination with oil or gas quenching [1]. The result of the heat treatment or rather the microstructure generated in the surface layer decisively determines the achievable load-carrying capacity of the component [1] as well as the performance and limitations of the usually last machining step in the process chain of component manufacturing – the grinding process [2]. In recent research a significant increase in load-carrying capacity of gears was achieved with an adapted case-hardening process, in which carburization is replaced by carbonitriding [1]. On the other hand, this kind of heat treatment usually leads to multi-phase surface layer microstructures with increased content (from typically less than 25 vol.% up to 70 vol.%) of retained austenite and many finely distributed hard precipitates, whose cost-effective and process-reliable hard fine machining presents a challenge.

Against this background, this paper deals with the machinability during discontinuous profile grinding (in the following called grindability) of differently case-hardened gears with various multi-phase microstructures. Both directions of action between grinding and microstructure were considered: effects of material phases, precipitates and their distribution in the surface layer on the grinding process as well as effects of thermal and mechanical impacts of the grinding process on resulting microstructural changes.

### 1.1. Discontinuous profile grinding of gears

Discontinuous profile grinding is a gear-grinding process widely used in industrial applications for finishing the tooth flanks of heat-treated gears [3]. If no angle-optimized grinding is used and no modifications are existing, the profile of the grinding wheel generally corresponds to the negative profile of the tooth gap of the workpiece in normal section and both tooth flanks of each gap are ground simultaneously. When grinding, the grinding wheel is aligned with the helix angle $\beta$ of the gear to the workpiece axis. The feed motion is effected by an exclusively axial movement in the case of a straight toothing and for $\beta \neq 0$ by consideration of an additional space component, since in this case the tooth flanks run as a helix along the cylindrical gear-base body [4].

In discontinuous profile grinding an elevated risk for grinding burn exists in comparison to alternative hard-finishing processes, which therefore represents a significant performance limiting factor of the process [3,5]. Due to relatively large contact lengths with additional uneven stock to be removed along the profile line and resulting locally varying stock removal rates, locally critically large heat flux into the component can occur and cause thermal damage to the microstructure. The surface layer microstructure defined by the heat treatment as well as the resulting component distortion, progressive grinding wheel wear and clogging of the tool pore space can increase this tendency.

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### *1.2. Potentials of multi-phase, novel case-hardened gears and known machining-relevant properties*

It is known from current research at the division Material Science of the Leibniz Institute for Materials Engineering that high-retained austenite contents in the surface layer (≥50 vol.%), which have been stabilized by carbonitriding, can have a positive effect on the load-carrying capacity of gears [1].

Carbonitrided spur gears with ≥50 vol.% retained austenite showed an increase of up to 15% in the pitting-load capacity compared to conventional case hardening via carburizing (cf. Fig. 1). Increases like this in load-carrying capacity can either extend the achievable service life, enlarge the transferable loads or reduce the dimensioning of the gear, thereby conserving resources.

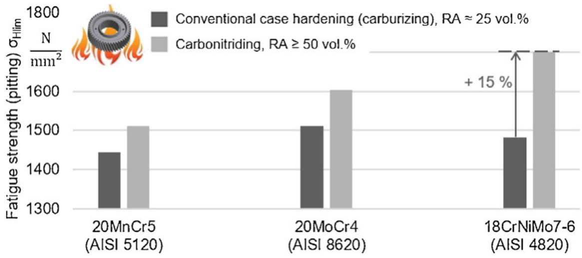


**Fig. 1.** Potentials of carbonitrided gears with high share of retained austenite (RA) for different investigated materials (according to Ref. [1]).

Unlike the previously mentioned variants, conventionally case-hardened gears have a martensitic surface layer microstructure with not significantly higher percentages than about 25 vol.% retained austenite. For these, the technological limits of gear grinding are largely known. In contrast to this, the described novel case-hardened variants with the potential to increase the load-carrying capacity are characterized by a multi-phase of martensite, partly bainitic portions and in particular a dominant fraction of retained austenite (≥50 vol.%). Consequently, for the work presented here, the machining-relevant properties of austenite are important. These include a comparatively high ductility and toughness, a relatively low thermal conductivity, which impedes the heat flow from the contact zone and a pronounced tendency of adhesion to the abrasive layer. The latter leads to increased clogging of the grinding wheel, the negative influence of which on grinding productivity is known [6]. In addition, the heat treatment results in a thin (10–20 μm) surface oxidation layer with decreased hardness and increased ductility which can further intensify the clogging, provided that case hardening has not taken place at low pressure. Carbonitrided surface layers are usually also characterized by an increased portion of precipitates such as carbides, carbonitrides or finely distributed nitrides, whose high hardness additionally promotes increased grinding wheel wear.

## 2. Experimental setup and procedure

In the research presented here, a total of 10 different variants of case hardening have been investigated together with a reference variant currently used in industry for gears, all of which have shown potentials for increasing strength compared to the reference. At the same time, the 11 heat-treatment variants shown in Table 1 enable the systematic investigation of various influencing variables on the grindability.

The heat treatment took place at our division Material Science. The varied parameters are the thermochemical heat-treatment process (gas carburizing, gas carbonitriding, low-pressure carbonitriding), the set content of retained austenite (25 vol.%, 50 vol.% and 70 vol.%, each at a depth of 50 μm), the tempering temperature (150 °C, 180 °C and 280 °C) as well as the present precipitates and their distribution (finely distributed and as grain-boundary carbide networks). In the following, the abbreviations for the individual heat-treatment variants introduced in Table 1 are used, which contain the essential properties of each variant. As mentioned above, the scope of experiments also includes a conventional reference variant, which means one that complies with current standards (DIN 3990 [7], ISO 6336 [8]). This variant was gas carburized, quenched in oil and tempered at 180 °C for two hours. The result is a microstructure with 25 vol.% retained austenite and a surface hardness of approx. 700 HV1. If the case hardening is varied on this basis according to the data in the table, the appearance of the surface layer structure changes significantly. Instead of the martensitic structure of the reference variant, a surface layer microstructure is formed in the strength-enhanced variants, which is dominated by retained austenite (≥50 vol.%).

To illustrate this, Fig. 2 compares the microsections of the gas-carbonitrided variant RA50 GCN T180 CB+ with those of the gas-carburized reference variant RA25 GCA T180. In addition to the increased retained-austenite content of approx. 50 vol.% in the surface layer, the special etching according to Murakami of the carbonitrided variant also reveals the increased precipitation content below the surface oxidation layer (cf. Fig. 2 – 2a). In this case there are many finely distributed chromium nitrides, whereby the resulting precipitation content is maximum for this variant.

In principle, however, all carbonitrided variants showed an increased portion of precipitates below the surface oxidation layer compared to the reference. The investigated variants RA50 LPCN T180 and RA50 LPCN T180 BCB were carbonitrided at low pressure, which prevented the formation of a surface oxidation layer. For the two variants with increased tempering temperature (RA50 GCN T280, RA70 GCN T280), it should be noted that in this case parts of the retained austenite are converted by tempering, so that the final retained austenite content is less than 50 vol.% respectively 70 vol.% (state directly after carbonitriding).

**Table 1**
Investigated heat treatments (material: 20MnCr5 (AISI 5120)).

| Used abbreviations | RA in vol.% [50 μm] | C in ma.% | N in ma.% | CHD[a] in mm | Heat treatment | Tempering |
|---|---|---|---|---|---|---|
| RA25 GCA T180 (Ref.) | 25 | 0.76 | 0.01 | 1.0 | Gas carburizing | 180 °C, 2 h |
| RA50 GCA T180 | 50 | 0.93 | 0.01 | 1.0 | Gas carburizing | 180 °C, 2 h |
| RA50 LPCN T180 | 50 | 0.79 | 0.49 | 1.0 | Low-pressure carbonitriding | 180 °C, 2 h |
| RA50 GCN T180 | 50 | 0.85 | 0.33 | 1.0 | Gas carbonitriding | 180 °C, 2 h |
| RA50 GCN T150 | 50 | 0.85 | 0.33 | 1.0 | Gas carbonitriding | 150 °C, 2 h |
| RA50 GCN T280 | <50 | 0.85 | 0.33 | 0.9 | Gas carbonitriding | 280 °C, 2 h |
| RA70 GCN T150 | 70 | 1.15 | 0.28 | 1.0 | Gas carbonitriding | 150 °C, 2 h |
| RA70 GCN T180 | 70 | 1.15 | 0.28 | 1.0 | Gas carbonitriding | 180 °C, 2 h |
| RA70 GCN T280 | <70 | 1.15 | 0.28 | 0.9 | Gas carbonitriding | 280 °C, 2 h |
| RA50 GCN T180 CB+ | 50 | 0.86 | 0.67 | 1.0 | Gas carbonitriding | 180 °C, 2 h |
| RA50 LPCN T180 BCB | 50 | 1.03 | 0.17 | 1.0 | Low-pressure carbonitriding | 180 °C, 2 h |

| | | | |
|---|---|---|---|
| RA | Retained austenite | GCA | Gas carburizing |
| GCN | Gas carbonitriding | LPCN | Low-pressure carbonitriding |
| T | Tempering temperature (°C) | BCB | Boundary carbides |
| CB+ | Increased percentage of precipitates (finely distributed) | | |

[a] CHD: Case hardening depth (standard deviation: ±0.05 mm).

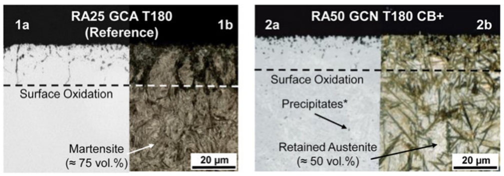


**Fig. 2.** Comparison of microsections (Fig. 2 – 1a, 2a: special etching according to Murakami; Fig. 2 –1b, 2b: Nital etching) of the conventionally case-hardened reference variant (left: Fig. 2 –1a, 1b) and a carbonitrided variant (Fig. 2 –2a, 2b) with many finely distributed precipitates (material: 20MnCr5 (AISI 5120)).

As mentioned before, the primary objective was to systematically investigate the machinability of the heat treatment variants presented and to evaluate it in comparison to the reference. For this purpose, a reference profile grinding process was defined with the help of preliminary tests with the reference variant RA25 GCA T180, whose grinding and dressing parameters deliberately lead to thermal microstructure damage even after a relatively low machined volume (cf. Fig. 3). This incipient grinding burn on the tooth flanks showed up reproducibly in four repeat tests after $30 \pm 2$ ground tooth gaps (tg), which corresponds to a related machined volume of $V'_W = 612 \pm 40\ mm^3/mm$. Subsequently, this reference process was applied to all 11 heat-treatment variants under identical conditions. Each grinding experiment corresponds to the discontinuous profile grinding (simultaneously on both flanks) of an entire gear (47 tooth gaps, $V'_W = 949\ mm^3/mm$), whereby dressing was carried out only once at the beginning of each experiment. At the same time, the measured quantities listed in Fig. 3 have been determined to assess the grindability of the various variants. Nital etching and Barkhausen-noise measurements were used to detect grinding burn, while X-ray residual-stress measurements and metallographic micrographs were utilized in selected samples and also to calibrate the two aforementioned methods.

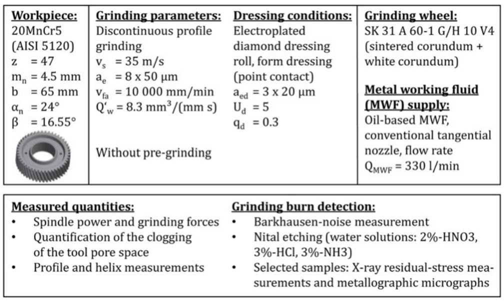


**Fig. 3.** Experimental setup (applied reference grinding process) and measured quantities.

The grinding tests were carried out on a Kapp KX 500 FLEX, which allows for the machining of gears with a diameter up to 500 mm and a maximum module of m = 10 mm. For process monitoring the machine is equipped with a three-component force dynamometer and an acoustic-emission measurement system. In addition, a gear-measurement system is integrated in the workspace of the machine tool, for the in-situ evaluation of the shape accuracy.

## 3. Results and discussion

According to the above data (Fig. 3), the reference grinding process was applied under identical conditions to all 11 heat-treatment variants. The evaluation of the increase in spindle power during grinding of the entire gear enabled an initial classification of the gear grindability of the 11 investigated variants. Fig. 4 illustrates two essential findings: On the one hand, the different surface layer microstructures resulting from different heat treatments obviously have a significant influence on the development of spindle power and on the other hand, the individual variants can be clustered into 6 groups. For each group of bars shown in the figure, the central red bar represents the respective mean value with associated standard deviation, whereby the

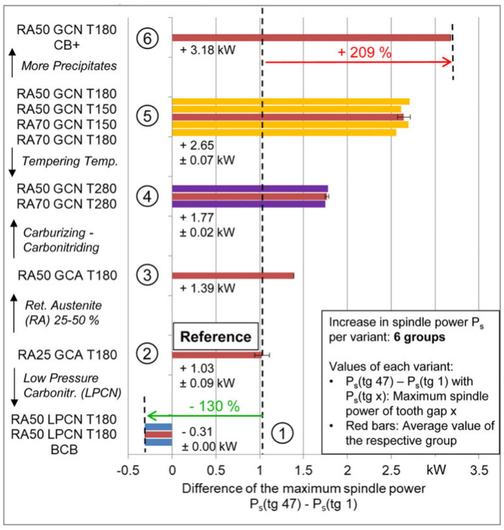


**Fig. 4.** Increase in spindle power between first and last (47th) ground tooth gap per heat-treatment variant and clustering of the 11 variants into 6 groups.

length of each bar corresponds to the increase in spindle power $P_s$ from the first to the last (47th) ground tooth gap.

It becomes clear that with the exception of Group 1, all strength-enhanced variants with an increased portion of ductile retained austenite in the surface layer (Groups 3–6) lead to a significantly elevated increase in spindle power compared to the reference (Group 2). By means of optical measurements at the grinding-wheel surface, it was additionally possible to show that with all these variants also an increased clogging of the tool pore space occurred. The largest increase in spindle power resulted for all gas-carbonitrided variants (Groups 4–6) and is maximum for variant RA50 GCN T180 CB+ (Group 6) with many finely divided precipitates (see Fig. 2) with a 209% higher increase than for the reference. The slightest increase for gas-carbonitrided gears can be seen for both variants with an elevated tempering temperature of 280 °C (Group 4), whereby this tempering treatment reduced the final content of retained austenite by transformation (see Table 1).

As mentioned above, Group 1, consisting of the two low-pressure carbonitrided variants without surface layer oxidation, is an exception, with the only two variants where the increase in spindle power is less than the reference. They are also the only variants in which the spindle power does not increase but even decreases slightly (0.31 kW or relatively −11.9%). This decrease is probably due to the grinding behavior during the first gaps (self-sharpening effects of the grinding wheel), so that a relatively constant spindle power can be observed. Also the clogging of the tool was significantly reduced compared to the reference. The development of spindle power as a function of increasing tool wear and the degree of clogging thus represents a first possibility to recognize various influences of the different variants related to material phases and heat treatment on the grindability (the essential differences are summarized on the left-hand side of Fig. 4 at the vertical arrows).

As mentioned before, the influence of the grinding process on the microstructure is also an essential part of this work. As an example, Fig. 5 shows microsections for the two extreme cases Group 1 and Group 6, each in comparison of the first and the last (47th) ground tooth gap. It becomes clear that, as was to be expected based on the increase in spindle power $P_s$, for Group 1 (low-pressure carbonitriding) no significant changes in microstructure can be detected from the first to the last ground tooth gap. On the other hand, a significant impact of the grinding process on the last ground tooth gap of the variant RA 50 GCN T180 CB+ (Group 6) is evident.

The machined volume up to the first detection of slight grinding burn on the tooth flanks $V'_{Wt}$ was also determined for each variant using the methods shown in Fig. 3 (particularly nital etching and Barkhausen-noise measurements). The results of this procedure are shown in Fig. 6 (values of the ordinate axis). The previously defined 6 groups can also be recognized here. Likewise, a

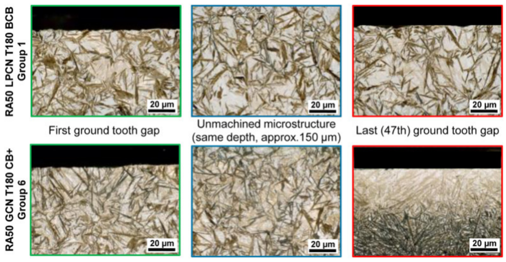


**Fig. 5.** Comparison of microsections of the first (left, green) and last (right, red) ground tooth gap for the two extreme cases Group 1 (RA50 LPCN T180 BCB) and Group 6 (RA50 GCN T180 CB+).

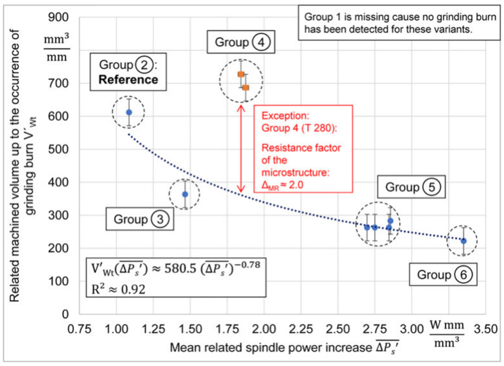


**Fig. 6.** Influence of the mean related spindle power increase $\overline{\Delta P_s'}$ (cf. Eq. (1)) on the resulting related machined volume up to the occurrence of grinding burn $V'_{Wt}$ for all defined groups.

dependence of this value $V'_{Wt}$ on the spindle power becomes clear if, according to Fig. 4 $\overline{\Delta P_s'}$, the mean related increase in spindle power per machined volume (cf. Eq. (1), is plotted. Since no grinding burn has been detected for the low-pressure heat-treated variants of Group 1, the points of these two variants are missing here. The deviating behavior of Group 4 of the two high-tempered variants is particularly noticeable in the figure. Despite a significantly higher increase in spindle power than for the reference variant (Group 2), grinding burn only occurred after a significantly larger machined volume (approx. +15%). Consequently, the two corresponding red dots are not part of the regression shown. With a coefficient of determination $R^2$ of about 92%, the functional relationship between the mentioned quantities for all other groups reads as follows:

$$V'_{Wt}(\overline{\Delta P_s'}) \approx 580.5\,(\overline{\Delta P_s'})^{-0.78}\ and\ \overline{\Delta P_s'} = \frac{P_s\,(tg\,47) - P_s\,(tg\,1)}{V'_W\,(tg\,47) - V'_W\,(tg\,1)} \quad (1)$$

For the two variants of Group 4 (T280, cf. Table 1), $\overline{\Delta P_s'}_{\_T280} \approx (1.86 \pm 0.03)$ W mm/mm$^3$ was measured on average, so that with the aid of Eq. (1), the theoretical expected value for the machined volume up to the occurrence of grinding burn can be calculated to $V'_{Wt\_T280\_expected}(\overline{\Delta P_s'}_{\_T280}) \approx (358 \pm 5)$ mm$^3$/mm. However, the measured value for this group $V'_{Wt\_T280\_measured}(\overline{\Delta P_s'}_{\_T280}) \approx (707 \pm 61)$ mm$^3$/mm deviates significantly. The microstructure of the high-tempered variants (thermally stabilized) is obviously characterized by greater resistance against the increased process temperatures resulting from clogging and wear of the grinding tool than the other heat-treatment variants. To take this "microstructure resistance" (MR) into account, a factor $\Delta_{MR}$ can be defined as follows:

$$\Delta_{MR} = \frac{V'_{Wt\_measured}}{V'_{Wt\_expected}\,(\overline{\Delta P_s'})} \quad (2)$$

This quantity indicates the factor by which the measured machined volume of the respective heat-treatment group deviates from the theoretical value of the regression and can be regarded as a measure of the resistance of the microstructure to damage caused by increased process temperatures due to clogging and tool wear. While for all other variants this aspect is negligible with a value of $\Delta_{MR} \approx 1$, the high-tempered and thermally stabilized variants with $\Delta_{MR\_T280} \approx 2.0$ show a clear deviation.

In summary, it can therefore be stated that there is a direct correlation between the increase in spindle power during grinding and the resulting machined volumes up to the occurrence of grinding burn $V'_{Wt}$ for all investigated variants. The exception is the Group 4 of high-tempered variants (T280), in which thermal damage to the microstructure occurs only at significantly higher degrees of clogging and resulting spindle power. This shows that both directions of action must be taken into account when assessing the grindability of different surface layer microstructures. The kind of microstructure determines the rate of change of the grinding process over time (e.g. increase of spindle power or clogging after dressing). Depending on the extent of these process variables as a function of the existing surface layer microstructure, different impacts of the grinding process (thermal and mechanical energy), which affect the surface layer, result. However, the extent to which it is affected by the given energy input depends on the degree of stabilization of the surface layer microstructure. According to the available results, the tempering treatment seems to be the most important influencing factor for this "microstructural resistance" $\Delta_{MR}$ (potential of the high-tempered variants).

## 4. Conclusion

In the investigations presented in this paper, a significant influence of the existing surface layer microstructure on the performance and technological limits of discontinuous profile grinding could be demonstrated. The total of 11 investigated variants could be divided into 6 groups with regard to their grindability. The thermochemical heat-treatment process carbonitriding, an increased residual-austenite content, as well as many finely distributed precipitates in the surface layer generally led to a negative effect, while heat treatment at low pressure (without the formation of a ductile surface oxidation layer) and an increased tempering temperature of 280 °C improved the grindability. It was found that spindle power is a suitable process variable for designing optimized dressing intervals during discontinuous profile grinding of the various investigated multi-phase, case-hardened gears with improved load-carrying capacity.

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