Material Properties and Tooth Root Bending Strength of Shot Blasted, Case Carburized Gears with Alternative Microstructures

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Introduction and Motivation

For most applications, components in transmissions with a high power density are case-hardened to provide a material strength which is suited to the load. The current methods commonly used for carrying out case hardening are gas and low-pressure carburizing in combination with oil or gas quenching. The heat treatment leads to a characteristic microstructure in the surface-near case layer, which significantly determines the achievable load carrying capacity properties of the gear. In the past few years, the technological development in the field of case hardening has been based on the optimization of the martensitic case layer structure. Through narrower limits and more precise definitions of the individual process steps, the range of the process outcomes has been narrowed down. Thus, the properties regarding load carrying capacity have increased within the scatter band of the achievable results, but overall, no effective growth due to the process of case carburizing was achieved.

In recent years, the main focus of the heat treatment of highly stressed, case hardened components has been on reproducibility and fulfilment of increasingly tight tolerances with regard to the carbon and hardness profile. Corresponding requirement profiles are defined in standards such as ISO 6336-5 (Ref. 11). The narrow tolerances with regard to the composition of the case layer show that the technological development of the microstructure for case carburizing is nearly exhausted. The development and testing of alternative microstructures and case layer conditions with the potential to increase the load carrying capacity have moved to the background of technological research.

In other areas of application, such as the heat treatment of rolling bearings, significant progress has been made. New impulses have been generated, for example, by the use of mixed microstructures containing bainite, martensite and retained austenite (Ref. 8) or bainitic microstructures, e.g. — "super bainite" (Ref. 3) — which have shown considerable potential for the improvement of load carrying capacities.

Most of the new approaches have improved the microstructure, which results in the increasing importance of this area of development. According to the state of the art, the essential components of the case layer should be mainly martensite and finely distributed retained austenite. But this assumption regarding case hardening is not unrestrictedly valid anymore. Preliminary tests in FVA 513 I (Ref. 14) showed that there are mixed case layer microstructures which, compared to state of the art, contained increased amounts of retained austenite of up to 60 % bainite or carbides. These mixed case layer microstructures can lead to an increase of the load carrying capacity. The application of carbonitriding as an alternative heat treatment process to carburizing has shown that the question of the stability of retained austenite is of central importance, and that the stabilization state is decisive for the strength properties of the microstructure. It should be noted in particular that microstructures with a balanced ratio of martensitic components with sufficiently stabilized austenite, bainite and retained austenite are promising.

This is the point where the research project FVA 513 III (Ref. 19) has connected. It investigated the problems identified in the literature and in the companies to develop and test new case layer microstructures. The aim of the project was to identify and safeguard increased strength properties of new case layer microstructures through heat treatment trials and structural-mechanical component tests on model samples and gearwheel tests. Selected results of this research project concerning the material properties and tooth root bending strength of shot blasted, case carburized gears with alternative microstructures are published in this paper.

State of the Art

Requirements of standards. The relevant gear standards, such as DIN 3990 (Ref. 4), ISO 6336 (Ref. 11) and AGMA 2001 (Ref. 2), respectively, and AGMA 923 (Ref. 1) specify the surface hardness and the microstructure, which have to be achieved for case hardened gears. However, these specifications are relatively brief and do not give any indication of a possible increase or reduction of the load carrying capacity, if these specifications are not complied with.

For the case hardening layer, the standards DIN 3990 (Ref. 4) and ISO 6336 (Ref. 11) intend a martensitic microstructure which must be fine-needled for material quality ME. According to ISO 6336 (Ref. 11), a bainite content of less than 10% is recommended for the material quality MQ; for the material quality ME, this limit value is a requirement. The AGMA 2001 (Ref. 2) and AGMA 923 (Ref. 1) contain separate specifications for the content of upper-bainite in the case hardening layer, for the load carrying capacities of tooth flank and tooth root. With regard to the surface durability, a maximum of 5% for grade 2, or only traces of bainite for grade 3, are permissible. For the tooth root bending strength, these limits are slightly shifted and a maximum of 10% bainite for grade 2 or 5% bainite for grade 3 is permissible.

According to DIN 3990 (Ref. 4), mesh and bone carbides are not permitted if they are visible at a magnification of 500 times. In ISO 6336 (Ref. 11), individual carbides with a maximum length of 0.02 mm are allowed for the material quality MQ, while only finely divided carbides are permitted for the material quality ME.

For the retained austenite content, DIN 3990 (Ref. 4) specifies a maximum amount of 30% for material quality MQ, or 20% for material quality ME. According to ISO 6336 (Ref. 11), the maximum retained austenite content of 30% is specified for both material qualities MQ and ME. Likewise, according to AGMA 2001 (Ref. 2) and AGMA 923 (Ref. 1), retained austenite contents of maximum 30% are permissible for grades 2 and 3.

Research project FVA 513 I. Research project FVA 513 I (Ref. 14) is the predecessor of the research project FVA 513 III (Ref. 19), which in turn is the basis of the results published in this paper. In the research project FVA 513 I (Ref. 14) different retained austenite contents were adjusted by means of carbonitriding. The influence of the different retained austenite contents on the load carrying capacity of the tooth root and flank was investigated in comparison to case hardened reference test gears. The focus of the investigations was on the materials 20MnCr5, 18CrNiMo7-6 and 20MoCr4. The results of the investigations regarding the bending strength are shown (Fig. 1).

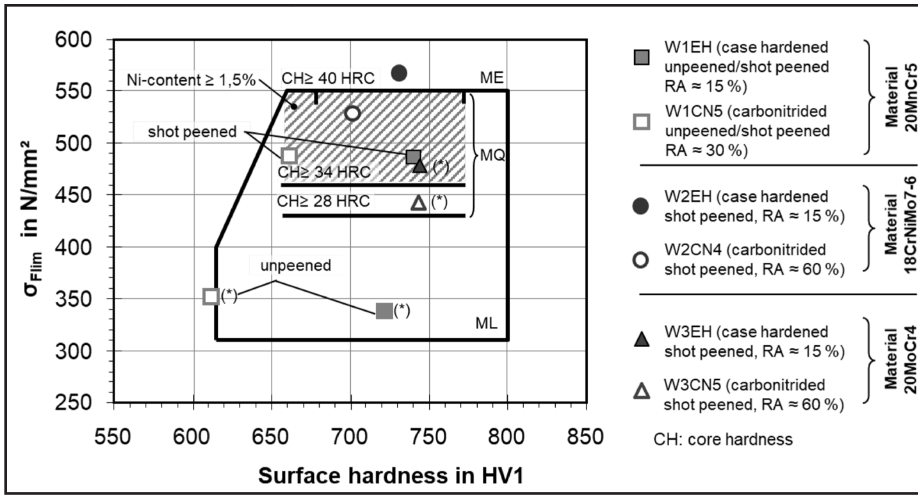


Figure 1 **Classification of the determined allowable bending stress numbers for carbonitrided gears with increased amounts of retained austenite in the standard strength diagram of DIN 3990 (Ref. 4) for case-hardened gears (*reduced data points, usually about half the data points).**

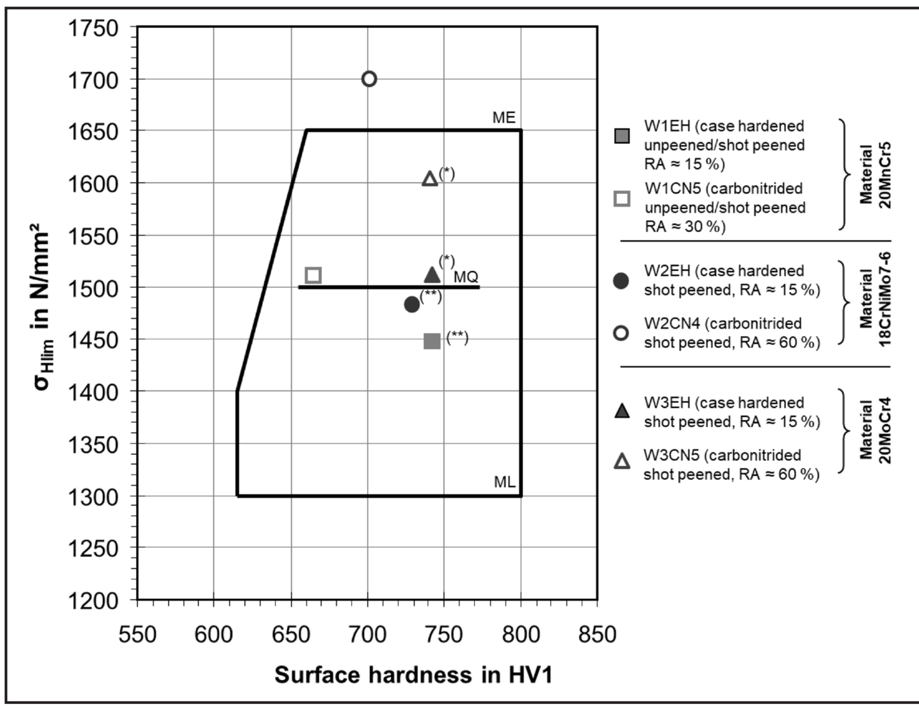


Figure 2 **Classification of the determined allowable contact stress numbers for carbonitrided gears with increased amounts of retained austenite in the standard strength diagram of DIN 3990 (Ref. 4) for case-hardened gears (*reduced data points, usually about half the data points; **comparison and good correlation with results from earlier investigations (Refs. 14, 20).**

For the material 20MnCr5, higher tooth root bending strengths tend to result both for the non-blasted and for the shot-peened condition of the carbonitrided variant compared to the case-hardened reference. For the materials 18CrNiMo7-6 and 20MoCr4, the results show a slight decrease of the tooth root bending strength in the carbonitrided state compared to the case hardened reference. However, these results are still within a typical range for shot-peened gears and have characteristic values of the material quality MQ. In the case of the 18CrNiMo7-6 variant, it should be noted that the case hardened reference has a very high bending strength.

With regard to the pitting load carrying capacity shown (Fig. 2), it can be seen that all variants in the carbonitrided state have a pitting load carrying capacity which is higher, and in some cases significantly higher, than the one of the case-hardened reference. The highest load carrying capacity was determined on the carbonitrided variant of the material 18CrNiMo7-6, which even exceeds the characteristic values for the material quality ME.

The results allow the conclusion that carbonitrided gears can show clear potential in the pitting load carrying capacity compared to the case-hardened reference. At the same time, the tooth root bending strength is not significantly reduced; indeed, in some cases, even a slight increase is possible.

The high-retained austenite variants of the materials 20MnCr5 and 18CrNiMo7-6 also showed promising results with regard to micropitting and wear. The scuffing load capacity was evaluated negatively, which, however, can be compensated by use of a suitable lubricant selection. Further details can be found in (Refs. 15 and 13).

Research project FVA 513 III. The publication with the title "Alternative Microstructures and Their Influence on Mechanical Properties of Case-Hardened Gears" (Ref. 10) has published selected information of the research project FVA 513 III (Ref. 19). The two variants with alternative case layer microstructures, which were compared to the reference variant, were made of the material 20MnCr5, gas carburized with different C-level and temperature controls, and mechanically cleaned by shot-blasting. Variant one had a case layer microstructure with 50% retained austenite and variant two with 30% bainite.

The flank load carrying capacity of the gears with the alternative microstructures showed a significantly increased pitting load carrying capacity in comparison to the case-hardened reference (Ref.10). The tooth root bending strength, by contrast, was not influenced in a negative way for the shot blasted gears. All in all, the results of the investigations of FVA 513 I (Ref. 14) could be confirmed, and prove that certain alternative microstructures in the case-hardened layer of gears do not necessarily have a negative impact on the load carrying capacity; in fact, they may even have a great potential to increase — especially the pitting load carrying capacity.

Retained austenite. By increasing the carbon content in a component during case hardening, it is possible to increase the residual austenite content under constant quenching conditions (Ref. 21). It can be seen from the literature that residual austenite contents of about 30% have positive effects on the flank load carrying capacity (Ref. 18) and the pitting load carrying capacity (Ref. 17) without causing a significant drop in the tooth root bending strength. Weck, Leng and Vinokur (Refs. 26–27) confirm the positive influence of highly retained austenite boundary layers on the pitting load carrying capacity, which is attributed to the good hardening capacity of austenite and finely distributed carbides. Strasser (Ref. 24) shows a small influence of the residual austenite content on the achieved tooth root bending strength of gears, whereby the effects occur less clearly in the shot-peened condition. Lechner (Ref. 12) describes the decrease of the scuffing load capacity for increased retained austenite contents due to the poorer thermal conductivity and the reduced adhesion of the lubricant in comparison to martensite. In addition, the reactivity of additives contained in the lubricant with the martensitic case layer is reduced due to increasing proportions of retained austenite (Ref. 9). Investigations of the micropitting resistance, on the other hand, show a positive influence of increasing retained austenite contents (Ref. 16).

In connection with the results from FVA 513 I (Ref. 14), this indicates that the state of the art guideline values for residual austenite contents of 25–30 % do not generally lead to the highest load carrying capacity results.

Bainite. Current developments in the field of rolling bearings (Ref. 25) indicate that a bainitic case layer can lead to improved properties concerning the load carrying capacity. A mixed structure of martensite and bainite produced by an incomplete isothermal transformation showed even stronger strength increases (Ref. 7). Similar results with partially bainitic case layers are kNown from a research project on the influence of the core hardness on the bending strength (Ref. 23).

Investigations on the tooth root bending strength (Ref. 22) have shown that a combination of too-high transformation temperatures and a clearly pronounced internal oxidation lead to a negative influence on the test results. A significant increase of the tooth root bending strength could be achieved by removal of the internal oxidation layer, as well as by shot peening. The choice of the carbon content in the case layer and the degree of bainitization are therefore of secondary importance.

Aim of Investigation

The microstructure of martensite and finely dispersed retained austenite is considered the standard for high-strength case layers. Investigations in the research project FVA 513 I (Ref. 14) have shown that a carbonitrided variant with a high content of retained austenite increases the tooth flank carrying capacity, while negative influences on the tooth root bending strength were not determined. Within a previous publication (Ref. 10) of the research project FVA 513 III (Ref. 19), the results of FVA 513 I (Ref. 14) were confirmed for two selected variants.

The aim of this report is to state the results of the investigations on further gear variants with alternative microstructures, such as material properties like hardness depth profiles, residual stress conditions and retained austenite contents, as well as their influence on the tooth root bending strength.

Test Program, Gears and Rigs

Test variants. Within the framework of the research project FVA 513 III (Ref. 19), different approaches were developed to generate alternative microstructures with the aim of raising the pitting load carrying capacity, while at the same time avoiding a negative influence on the tooth root bending strength.

The following alternative microstructures conditions were examined in detail:

- High retained austenite contents above 50% due to increased carbon or nitrogen contents, in combination with intermediate phase fractions
- Carbonitriding with optimized thermal post-treatment
- Generation of increased bainite contents of up to 30% in the case-hardening layer
- Creation of a specific variant with adjusted grain boundary carbides

Each variant with a different alternative microstructure is made of the case-hardening steels 20MnCr5 and 18CrNiMo7-6. Due to the low sulphur content in the investigated 20MnCr5 material, very few inclusion failures occur. In addition, it appears that the material achieves better results than a material with a comparatively high sulphur content. The material 18CrNiMo7-6 is strongly segregated, making heat treatment more difficult — especially during the carburization and subsequent bainitic transformation. In order to compare the heat treatment processes that were carried out, a case-hardened reference variant was developed for each test material; a summary of the test variants is shown (Table 1).

Test gears. For the pulsator test gears used in the experimental load carrying capacity investigations, there is an

Table 1 Test variants

Material	Variant	Designation	Heat Treatment	Quenching	Tempering
20MnCr5 + 18CrNiMo7-6	case carburized	R	gas carburizing	60°C, oil	180°C, 2h
	50% retained austenite gas carbonitrided	RA50GCN	gas carbonitriding	60°C, oil	180°C, 2h
	50% retained austenite carbonitrided	RA50LPCN	low pressure carbonitriding	10 bar, nitrogen	180°C, 2h
	10% bainite	B10	case austempering	T_B, salt	180°C, 2h
	50% retained austenite and optimized thermal post treatment at 150°C	TPT150	gas carboni triding	60°C, oil	150°C, 2h
	50% retained austenite and optimized thermal post treatment at 280°C	TPT280 carbonitriding	gas	60°C, oil	280°C, 2h
	grain boundary carbides	C	low pressure carburizing	60°C, oil	180°C, 2h

extensive kNowledge base at the institute, since this specific geometry has already been used in a large number of research projects. Therefore, the connection to already completed and ongoing research projects, as well as existing load carrying capacity standards, is guaranteed. The gear cutting of the pulsator test gears was carried out with the aid of a hob in protuberance design. For the correlation to industrial manufacturing processes, as well as to the specifications of the standards and their load carrying capacity values, after the heat treatment all test gears were mechanically cleaned by shot blasting in accordance with industrial practice. Neither the flanks nor the tooth root areas of the test gears were grinded after the heat treatment. An overview of the most important geometry data, as well as a geometry draft, is provided (Table 2).

Table 2 Main geometry data of the pulsator test gears

Description	Symbol	Unit	Value	Test gear
normal module	m_n	mm	5	
number of teeth	z	[-]	24	
tooth width	b	mm	30	
normal pressure angle	α	°	20	
helix angle	β	°	0	

Figure 3 Pulsator test rig with exemplary gears similar to the test gears.

The case-hardening steels 20MnCr5 and 18CrNiMo7-6 were used for the investigations; these materials are commonly used steels in the gear industry. The corresponding requirements for the materials on delivery were defined as follows:

- Chemical composition and documentation according to DIN EN 10084 (Ref. 5)
- Delivery condition: verification in the form of a 3.1 certificate according to EN 10204 (Ref. 6)
- Minimum degree of deformation 4, degree of deformation 6 should be aimed at
- Limited hardenability scatter band according to H- or HH
- Material quality ME according to ISO 6336-5 (Ref. 11)

The complete manufacturing process of the test gears, as well as the initial condition of the semi-finished products of the materials, were comprehensively documented.

Test rigs. The bending fatigue tests were carried out by means of an electromagnetic pulsating test rig (Fig. 3), and described in the following, according to (Ref. 10): the test rig consists of a machine frame that incorporates test device, load cell and test gear. The pulsating load is generated by a dynamic actuator that is connected to a dynamic spring by the exciting magnet, which is directly connected with the pulsating crossbeam by two-rod springs. The test gears were symmetrically clamped and tested over four teeth between two jaws. The exact position of the test gear in relation to the clamp jaws, i.e. — the exact angle and point of load incidence — was adjusted by means of a special jig. Flank angle deviations were compensated by means of a precision adjustment so that a uniform load distribution across the whole face width can be assumed. The test gear was friction-locked between both jaws, therefore an underload was needed that was always lower than 10% of the test load. The test runs were stopped after $6 \cdot 10^6$ load cycles.

Results

Material Properties

Microstructure. When considering the case layer microstructure in the tooth root in the non-etched state, the following is noticeable: the internal oxidation depth of the 20MnCr5 material variants (with the exception of the 20MnCr5 variant RA50LPCN, no internal oxidation due to the heat treatment process) is always higher in comparison with the variants of the material

Table 3 Exemplary comparison of internal oxidation in the tooth root, non-etched.

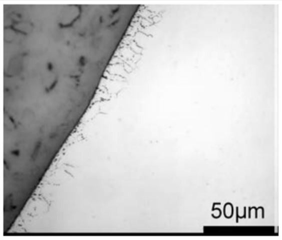
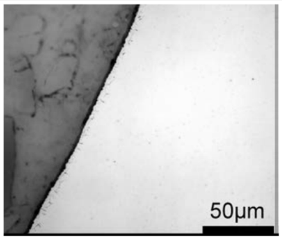
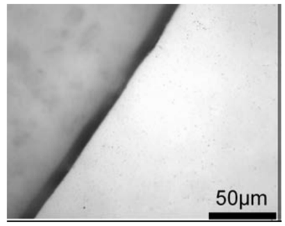
Reference – R	Reference – R	50% RA low pressure carbonitrided – RA50LPCN
		
Material: 20MnCr5	Material: 18CrNiMo7-6	Material: 18CrNiMo7-6

Table 4 Case layer microstructures of the variants made out of 20MnCr5.

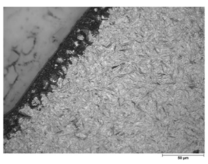
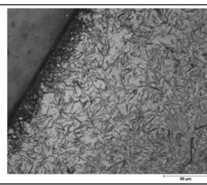
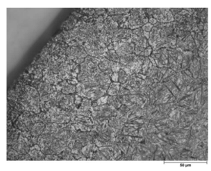
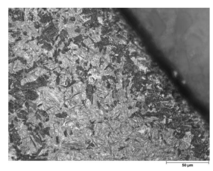
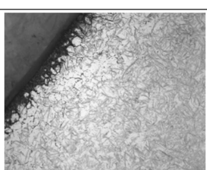
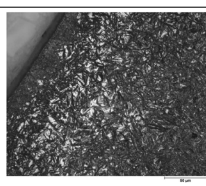
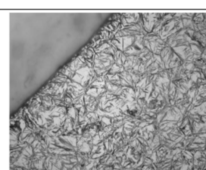
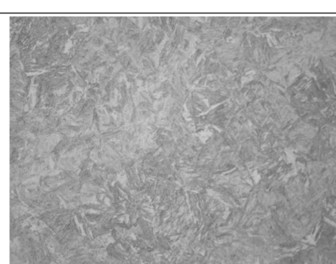
Material 20MnCr5			
Reference – R	50% RA gas carbonitrided – RA50GCN	50% RA low pressure carbonitrided – RA50LPCN	10% bainite – B10
			
martensite with 10 – 20% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 40 – 50% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 40 – 50% metallographically determined retained austenite	martensite with 10 – 20% metallographically determined retained austenite and non-martensitic case layer microstructure, area with locally increased bainite or troostite content
optimized thermal post-treatment at 150°C – TPT150	optimized thermal post-treatment at 280°C – TPT280	grain boundary carbides – C	
			
martensite with 50 – 60% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 0 – 10% metallographically determined retained austenite and non-martensitic case layer microstructure	martensite with 50 – 60% metallographically determined retained austenite and carbides	

Table 5 Exemplary core microstructure of the materials 20MnCr5 and 18CrNiMo7-6.

Reference – R	Reference – R
	
Material: 20MnCr5	Material: 18CrNiMo7-6

18CrNiMo7-6. Maximum internal oxidation depths for the material 20MnCr5 varies from 15–25 µm, and the material 18CrNiMo7-6 varies from 5–10 µm. Table 3 shows exemplary photographs.

In Table 4, detailed microstructure images of the variants made from the material 20MnCr5 are shown, along with a short description of the microstructure. The variants made from the material 18CrNiMo7-6 show very similar case layer microstructures and are thus not specifically depicted. The reference R made of the material 20MnCr5 shows a case layer microstructure of martensite with 10–20% metallographically determined retained austenite and a non-martensitic case layer microstructure. This microstructure is typical for a case-hardened gear. The variants with 50% retained austenite, carbonitriding RA50GCN and low-pressure carbonitriding show high amounts of retained austenite at metallographically determined 40–50%. The case layer microstructure of the variant with 10% bainite B10 consists of martensite with 10–20% metallographically determined retained austenite, bainite and a non-martensitic case layer microstructure. The image shows an inhomogeneous microstructure and segregations with areas of locally high bainite content, as well as troostite resulting from the heat treatment. For the variant with an optimized thermal post-treatment at 150°C TPT150, the microstructure is comparable to the variants RA50GCN, as well as RA50LPCN with additionally, finely divided carbides recognizable. For the variant with an optimized thermal post-treatment at 280°C TPT280, the initially high amounts of retained austenite were converted by the thermal post-treatment, resulting in significantly lower retained austenite value of metallographically determined 0–10%. The carbides variant C shows high retained austenite amounts of metallographically determined 50–60%, as well as grain boundary carbides.

The core microstructure of the material 20MnCr5 shows for all heat treatment variants a bainitic structure, whereby more upper- as lower-bainite is present. All the core microstructures of the material 18CrNiMo7-6 show a bainitic structure, where lower than upper-bainite is present. This correlates with the different core hardness values of the two materials. Exemplary core microstructures of the reference variants R of both materials are shown in Table 5.

Hardness. The determination of the hardness depth gradients was carried out at the left and right side of the flank and root of an unloaded, non-grinded and shot blasted pulsator wheel tooth. Table 6 shows the hardness depth profiles for all variants made of the material 20MnCr5. The hardness depth profiles of the material 18CrNiMo7-6 were comparable to the profiles of the material 20MnCr5. The two main difference were that the values of the core hardness at the flank and tooth root were more comparable and did not deviate as much for the material 18CrNiMo7-6 as the core hardnesses of the material 20MnCr5, and that the values of the core hardness of the material 18CrNiMo7-6 were consistently 50–150 HV1 higher than the values of the material 20MnCr5. Both observations correlate to the higher hardenability of the material 18CrNiMo7-6, compared to the material 20MnCr5.

All variants with exception of the variant with 10% bainite B10 show steady hardness depth profiles with limited scatter. The hardness depth profiles of the tooth flank and tooth root are comparable for the variants RA50LPCN and C. For the other variants, the hardness depth profiles of the tooth root are comparable to the tooth flank near the surface, but decrease stronger towards the core. The hardness depth profiles of the right and the left side of the tooth flank and the tooth root compare very well, with exception of the variant with 10% bainite B10.

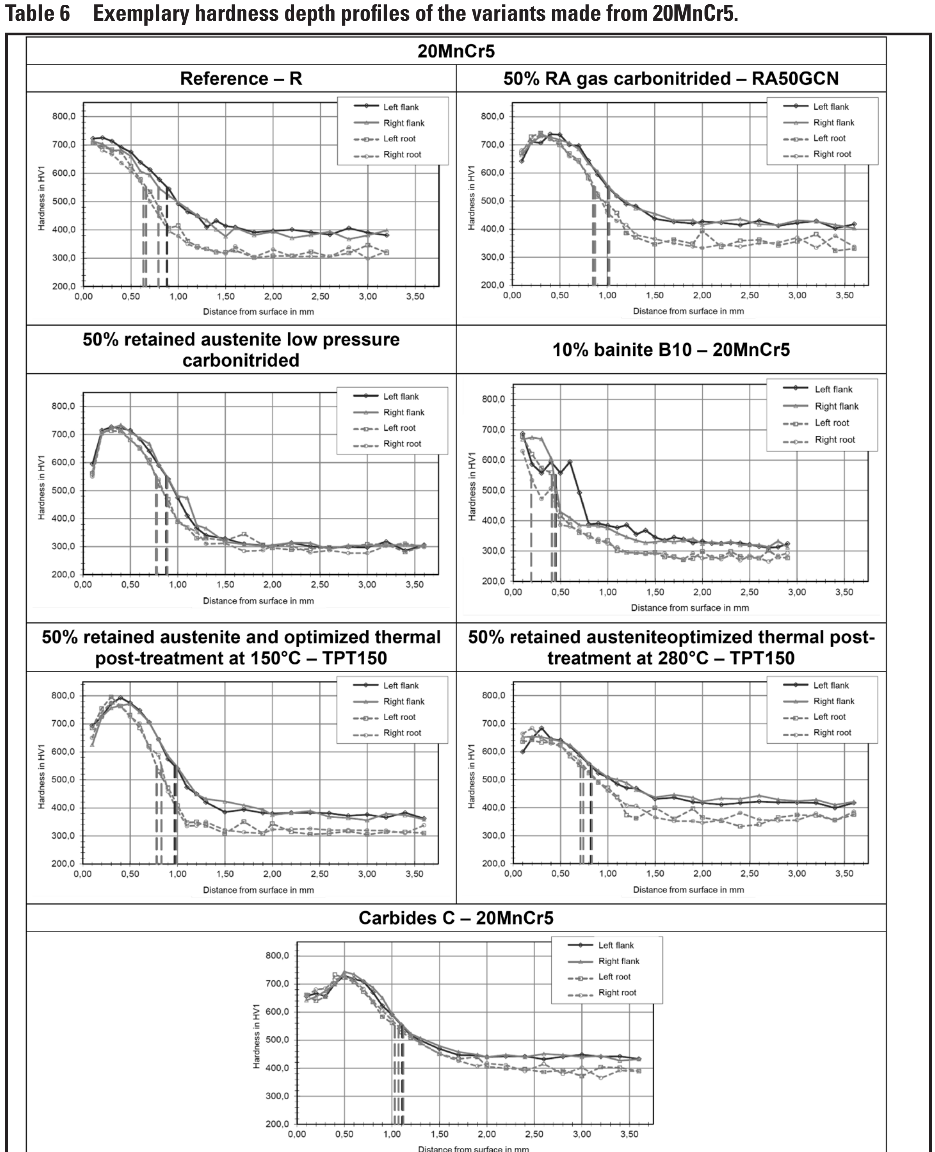
The reference R shows a hardness depth profile, which is typical for case-hardened gears of this size and material. The surface hardness measured in a material depth of 0.1 mm is approximately 700 HV1 and the case-hardening depth (CHD) with a hardness limit of 550 HV is in a range of 0.6–0.9 mm, which is inside the common recommendation of $CHD_{550HV} = 0.1–0.2 \cdot m_n = 0.5–1.0$ mm. Within the range, the tooth root shows the smaller CHD values compared to the flank. The core hardness values range from 300 HV1 for the tooth root to 400 HV1 for the tooth flank.

The variants RA50GCN, RA50LPCN, TPT150 and C all show a decrease of the hardness values towards the surface, which correlates with high-retained austenite contents. The surface hardness values range from 570 HV1 for the tooth root of RA50LPCN to 700 HV1 for the tooth flank of TPT150. The variant TPT280 with low-retained austenite contents does not show a hardness decrease towards the surface, but rather states a steady plateau at around 650 HV1. For the variants RA50GCN, RA50LPCN, TPT150 and TPT280 the core hardness ranges between 300–400 HV1, and the CHD ranges between 0.7–1.0 mm. The core hardness of the carbon variant C ranges from 400 HV1 for the tooth root values to 450 HV1 and the CHD reaches values of 1.0 –1.2 mm.

The largest differences in the measured hardness depth profiles are shown by the variant with 10% bainite B10 where, due to the inhomogeneous microstructure and segregations, strong fluctuations occur in the hardness measurements. The surface hardness has larger differences between the right and the left tooth root, where the surface hardness scatters from 630–690 HV1. The CHD is below the recommended minimum value of 0.5 mm and the core hardness ranges from 280 HV1–340 HV1.

The bar graphs in Table 7 show the determined surface and core hardness of all the variants examined. The variants of the material 20MnCr5 tend to show slightly higher-determined surface hardness in comparison to the material 18CrNiMo7-6. The highest surface hardness with values of almost 700 HV1 can be found for the reference

Table 6 Exemplary hardness depth profiles of the variants made from 20MnCr5.



of both materials. The variant with 50% retained austenite and low-pressure carbonitriding RA50LPCN shows the lowest surface hardness values for the material 20MnCr5 and for the material 18CrNiMo7-6, the variants with 50% retained austenite and carbonitriding RA50GCN, and even more the carbides variant C show a surface hardness of less than 600 HV1. For the individual variants, it is pointed out that there can be hardness reduction towards the surface. The minimum requirement for surface hardness of case-hardened gears according to part 5 of ISO 6336 (Ref. 11) is 660 HV1, which is not reached by some variants. Regarding the core hardness, the majority of the variants made of the material 18CrNiMo7-6 show an almost identical core hardness, which is about 440 HV10, and in a usual range for this material at the given gear size. The relatively low core hardness of the variant with 10% bainite B10 made of the material 18CrNiMo7-6 is a result of the heat treatment. The core hardness of the variants of the material 20MnCr5 assumes values at around 300 HV10 to 370 HV10, and is therefore always below the core hardness of the corresponding variant made of 18CrNiMo7-6. The comparatively high core hardness of the carbides variant C of the material 20MnCr5 is based on the quenching carried out (oil quenching).

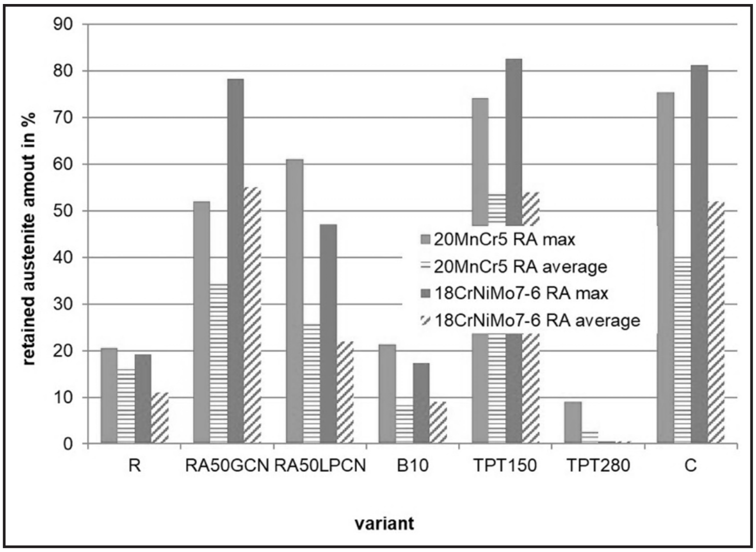


Figure 4 **Comparison of the radiographically measured retained austenite amount, maximum and average values.**

Residual stress and retained austenite. Table 8 shows a comparison of the residual stresses measured by an X-ray diffractometer at the surface, as well as the occurring maximum residual compressive stresses in the area of the 30° tangent in the tooth root. On the surface, all variants show residual compressive stresses, which occur in a range of −300 up to −500 N/mm². The occurring residual compressive stress maxima include a range from −450 up to −700 N/mm². In addition, for each variant the material depth position of the maximum residual compressive stress is shown in µm. It turns out that for all variants the maximum residual compressive stress is very close to the surface, which correlates with the shot blasting treatment.

Figure 4 shows the residual austenite content of the shot blasted pulsator test gears based on measurements of an X-ray diffractometer. The maximum values, as well as the average retained austenite contents over a material depth of 20–200 µm, are displayed. The first 20 µm are not taken into account for the average, since there is a non-martensitic case layer microstructure present in this surface near layer and the result would be falsified. Overall, there is a very large variation regarding the retained austenite content. The references R lie in a typical area for the present heat and shot-blasting treatment. Furthermore, the high retained austenite contents of the carbide variants are noticeable. This correlates with the increased carbon content in the case layer. For the variants with a thermal optimized post-treatment, the extreme decrease of the retained austenite content between the tempering temperatures 150°C and 280°C is remarkable. This result is the consequence of further conversion of residual austenite

Table 7 **Summary of the measured surface and core hardness values.**

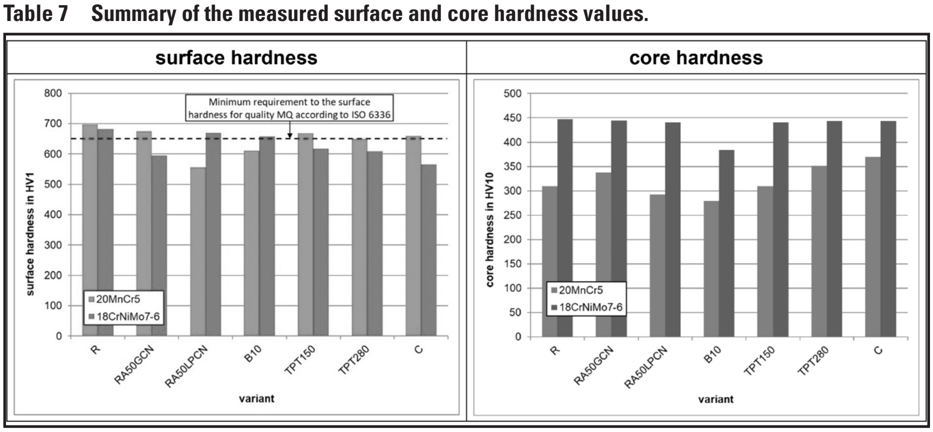
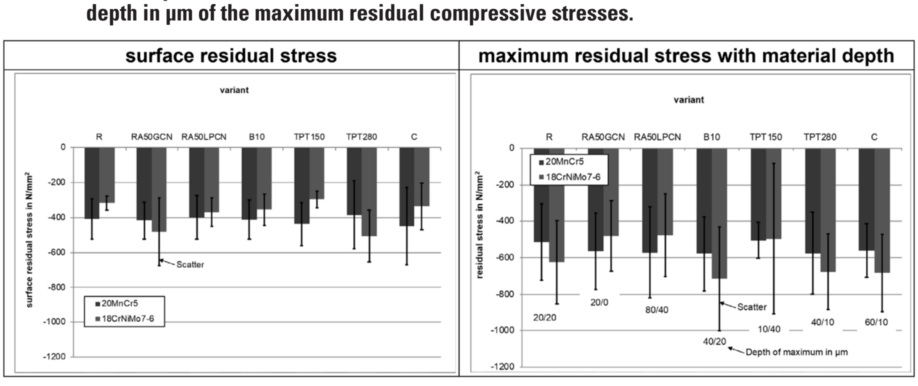


Table 8 **Summary of the measured surface and maximum residual stresses as well as the material depth in µm of the maximum residual compressive stresses.**



into martensite and bainite at the temperatures of 280°C, and has been confirmed in FVA 513 I (Ref. 14).

Tooth Root Bending Strength

Results of the test variants. Figure 5 shows the nominal tooth root bending strength for a failure probability of 50% ($\sigma_{F0\infty,50\%}$) of all investigated variants in a bar chart and compares the results with the case-hardened references R. In addition, the scatters of the individual variants, as well as a scattering range of ± 5% around the nominal tooth root bending strength of the case-hardened reference made of the material 20MnCr5, is depicted; it shows that the results of all variants lie within the illustrated scatter range. Furthermore, all variants show a test scattering that is still common for case-hardened gears. Overall, it can be said that the different heat treatment processes and alternative microstructures do not have a significant negative influence on the tooth root bending strength concerning long life for the shot-blasted condition. In the present case, a few variants made of the material 18CrNiMo7-6 tend to show higher scatters than the variants made of the material 20MnCr5. The higher scatters of the variants made of the material 18CrNiMo7-6 are presumably due to inhomogeneities in the base material. For all results it must be taken into account that the test gears were mechanically cleaned by shot-blasting and that the shot-blasting treatment may influence or cover up certain other effects such as different surface hardnesses or internal oxidation.

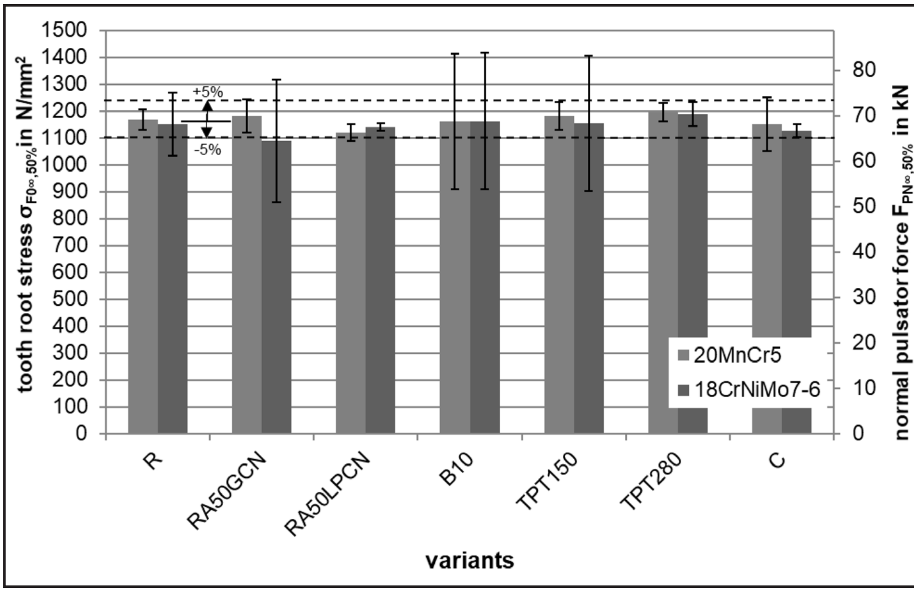


Figure 5 Results of the nominal tooth root bending strength at a 50% failure probability ($\sigma_{F0\infty,50\%}$) for all test variants.

Table 9 Results of the low nominal tooth root bending strength for limited life at a failure probability of 50% and the corresponding scatter for all variants.

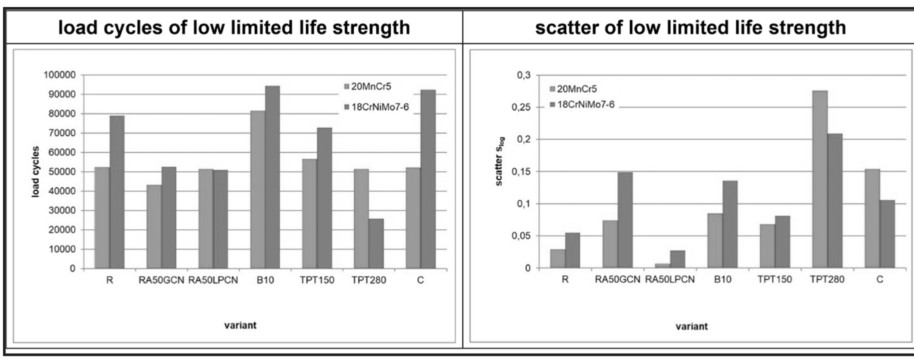
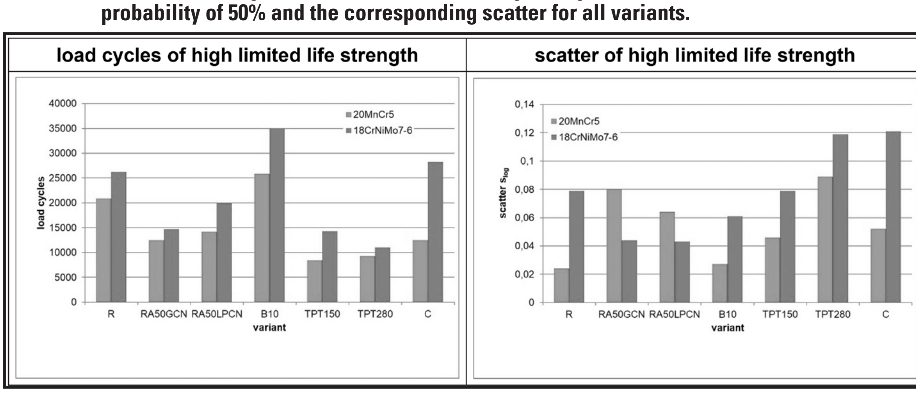


Table 10 Results of the high nominal tooth root bending strength for limited life at a failure probability of 50% and the corresponding scatter for all variants.



The results in the limited life range were examined more closely. Tables 9 and Table 10 show the average number of cycles to failure achieved for a failure probability of 50 % for the low and high limited life strength. In the limited life part of the S-N curve, measurements on two load levels where performed, i.e. — one measurement on a high load level with lower numbers of cycles and one measurement on a low load level with higher numbers of load cycles. The tests in the low limited life strength were performed at a pulsator normal force of $F_{Pn} \approx 80\,kN$ respectively $\sigma_{F0} \approx 1{,}350$ N/mm² and in the range of high limited life strength at $F_{Pn} \approx 95\,kN$ and $\sigma_{F0} \approx 1{,}600$ N/mm². Additionally, the logarithmic scatters s_{log} are shown. With the low as well as the high limited life strength, there are clear differences between the variants.

Most variants made of the material 18CrNiMo7-6 tend to have longer running times than the comparable variants made of the material 20MnCr5. In the area of low limited life strength, the variants with 10 % bainite B10 and the carbides variant C made of the material 18CrNiMo7-6 and for the material 20MnCr5 the variant with 10% bainite B10 have the highest numbers of load cycles. The variant with optimized thermal post-treatment at 280°C TPT280 made of the material 18CrNiMo7-6 achieved the shortest number of load cycles, whereby the very high scatter of this variant has to be taken into account. For the material 20MnCr5, the variant with 50% retained austenite and carbonitriding RA50GCN shows the lowest number of load cycles, while showing a scatter comparable with the case-hardened reference variant.

For the high limited life strength, the variants with 10% bainite B10 and the carbides variant made of 18CrNiMo7-6, as well as the variant with 10% bainite B10 made of 20MnCr5, have the highest numbers of load cycles. They exceed the number of load cycles of the respective case-hardened references. This characteristic can be observed at the low limited life strength as well. The variants with an optimized thermal post-treatment at 150°C TPT150 and 280°C TPT280, as well as the variant with 50% retained austenite and gas carbonitriding RA50GCN made of 18CrNiMo7-6, achieved the lowest numbers of load cycles. For the material 20MnCr5, the variants with an optimized thermal post-treatment at 150°C TPT150 and 280°C TN150, as well as the carbides variant C, showed the lowest running times with a slightly higher scatter compared to the case-hardened reference.

All the variants examined show a comparable tooth root bending strength for long life compared to the references R for both materials. However, in some cases, there are clear differences in the area of limited life strength. All variants show a nominal tooth root bending strength for long life at a 50% probability of failure, which is within the range of expectations for case-hardened, shot-blasted gears of this gear size. Taking into account the test scatter in the limited life strength range, no significant influence on the tooth root bending strength by the respective alternative microstructure states could be determined on the basis of the available pulsator tests. It should be noted, however, that all test gears examined had a tooth root area that was mechanically cleaned by shot blasting. The residual compressive stresses introduced by the shot-blasting in the area near the surface may have resulted in covering individual influences of the different microstructure variants. With regard to the conditions of the load carrying capacity according to the standard ISO 6336, part 5 (Ref. 11), it should be mentioned that the tooth root load carrying capacity values for gearwheels specified in this standard are applicable for a shot blasted condition and therefore the load carrying capacity values determined in this research work can be directly compared to the values of the standard. In the area of limited life strength, it can be assumed that the influence of the residual stresses induced by the shot-blasting decreases with increasing stress. The microstructure and hardness properties come more to the foreground as the load rises. This explains the partly different load carrying capacity properties of the individual variants in the area of tooth root bending strength for long life and limited life. It should be noted, however, that there is a statistically limited coverage, especially in the area of limited life strength. Particularly noteworthy is the variant with 10% bainite, which has a higher limited life strength for both materials than their respective case-hardened reference; this is attributed to the high toughness of the microstructure.

A detailed examination of the fractures of the carbide variants C in the cross-section shows that the crack runs along the grain boundary carbides. An exemplary crack course is shown (Fig. 6) for the variant made of the material 20MnCr5.

Classification into the State of Art and Discussion

The experimental investigations concerning the tooth root bending strength in the previous project FVA 513 I (Ref. 14) were carried out on pulsator test gears in non-blasted or specifically shot-peened condition. Among others, the case-hardened, shot-peened reference variants W1EH made of 20MnCr5 and W2EH made of 18CrNiMo7-6, as well as the carbonitrided, shot-peened variants W1CN5 made of 20MnCr5, and W2CN4 made of 18CrNiMo7-6, each with a high content of retained austenite in the case layer, were investigated. The variants made of 20MnCr5 additionally underwent investigations on the tooth root bending strength with a non-blasted condition. For the material 20MnCr5, comparable tooth root bending strength values could be determined for case-hardened and carbonitrided conditions. This applies to both the non-blasted and the shot peened condition. As seen (Fig. 7), the variants of the material 20MnCr5 investigated in the current project show almost identical tooth root fatigue strength values for case-hardened and gas carbonitrided

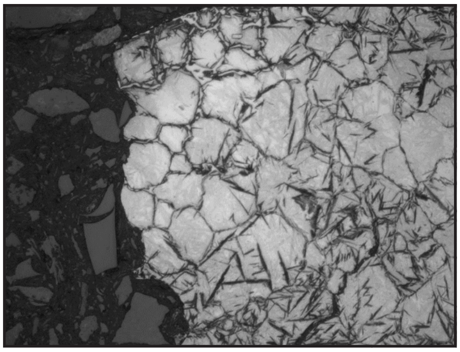


Figure 6 Exemplary illustration of the crack course of a tooth root fracture in the cross-section of the carbide variant C made of the material 20MnCr5.

Figure 7 Comparison of the results of the tooth root bending strength of case-carburized and gas carbonitrided gears with different blasting treatments.

conditions with high contents of retained austenite. The test wheels were examined in a shot blasted condition. In FVA 513 I (Ref. 14), the ned gears made out of 18CrNiMo7-6 show a slightly higher tooth root bending strength for the case-hardened material compared to the carbonitrided material. In FVA 513 III (Ref. 19), the tooth root bending strength of shot-blasted gears made out of 18CrNiMo7-6 showed that the case-hardened variant is also slightly stronger than the gas carbonitrided variant. The results prove that the tooth root bending strength of the material 20MnCr5 is almost identical for the respective blasting state in both the case-hardened and the gas-carbonitrided state. For the material 18CrNiMo7-6, it can be seen that the tooth root bending strength for the carbonitrided variants are slightly below those of the case-hardened variants. This applies to both the shot-blasting and the ning. In addition, it should be noted that the tooth root bending strength values of the material 20MnCr5 are almost identical for the shot-blasted and ned condition, whereas in the case of the material 18CrNiMo7-6 a clear increase in the load-bearing capacity is proven by ning. At the same time, a possible influence of the material and heat treatment batch cannot be excluded. Overall, it can be seen that the tooth root bending strength increases significantly as a result of a blasting treatment. The characteristic values for the long life strength lie within the usual range according to the state of kNowledge for a respective blasting state. Thus it can be shown that the results from FVA 513 III (Ref. 19) are in good agreement with the results from FVA 513 I (Ref. 14). In comparison to the respective case-hardened reference, no significant reduction of the tooth root bending strength by carbonitriding with a high-retained austenite content was found.

In Figure 8, the determined tooth root bending strength values of the individual variants are entered in the standard strength diagram according to ISO 6336 (Ref. 11). The variants marked with * are estimated strength values based on fewer data points. For additional comparison, strength values for case-carburized and shot-blasted gears made of the material 18CrNiMo7-6 and case-carburized and shot-blasted gears made of the material 16MnCr5 are given from the literature (Ref. 16). As stated, the tooth root bending strength values are all within a scatter range, which would still be common for case-hardened gears. Within this scatter range, the variant with an optimized thermal post-treatment at 280°C TPT280 made of 20MnCr5 has the highest, and the variant with 50% retained austenite and gas carbonitriding has the lowest tooth root bending strength.

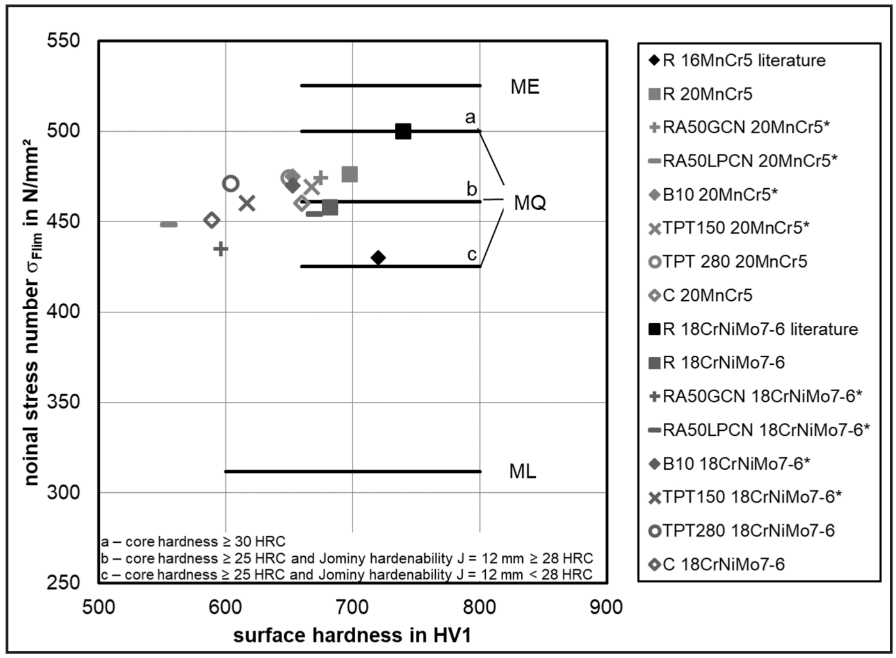


Figure 8 **Classification of the determined allowable contact stress numbers for the examined variants in the standard strength diagram of ISO 6336 (Ref. 11) for case-hardened gears (*reduced data points, additional values from literature [Ref. 16]).**

Conclusion

According to the current state of knowledge and previous experience, a case layer microstructure consisting of martensite and less than 30% retained austenite is considered highly sustainable. In the past, a lot of development work was done in the field of case-hardening with the aim of optimizing this case layer microstructure to meet the requirements of highly stressed components such as gears.

In the context of the research project FVA 513 I (Ref. 14), it was shown that a carbonitrided variant with a high-retained austenite content of up to 65% showed an increased tooth flank load carrying capacity without negative influence on the tooth root bending strength.

On the basis of these results, alternative case layers to the ones specified in standards such as ISO 6336 (Ref. 11) were specifically selected for this present paper. The shot-blasted gears with alternative microstructural conditions were investigated in detail concerning material properties and their influence on the tooth root bending strength.

The main results of these investigations are presented in the following conclusions:

- Gears with alternative microstructures that show inhomogeneities and segregations lead to unsteady and fluctuating hardness depth profiles, and possibly undesirable case-hardening depths.
- The variants with alternative microstructure made out of the material 20MnCr5 show greater fluctuations in the hardness depth profiles and values, compared to the respective variants made of the material 18CrNiMo7-6.
- The maximum residual compressive stresses of the shot-blasted gears with alternative microstructures lie relatively near to the surface.
- The shot-blasted gears of the carbides variant C did not fail prematurely, as assumed due to the internal notch effects of the carbide precipitates on the grain boundaries, but show a comparable tooth root bending strength as the case-hardened reference.
- In the limited life range of shot blasted gears, and with the exemption of the variant TPT280, the variants made of 18CrNiMo7-6 have a higher tooth root bending strength compared to the variants made of 20MnCr5.
- In the limited life range of shot-blasted

gears and comparing within one material, the microstructure can increase or decrease the tooth root bending strength significantly.

- When applying shot-blasting after the heat treatment, the examined alternative microstructures do not lead to a significant increase, nor to a decrease of the tooth root bending strength for long life.
- The tooth root bending strength values for long life are comparable and do not show any significant differences between the materials 20MnCr5 and 18CrNiMo7-6.
- Regarding the tooth root bending strength, certain alternative microstructures, which are different to the recommendations of part 5 of the standard ISO 6336 (Ref. 11), can be tolerated — especially if the gears are designed for long life. Additionally, the alternative microstructures may have a high potential to increase the tooth flank (contact) load carrying capacity.

For more information.
Questions or comments regarding this paper? Contact Jakob Winkler at *j.winkler@fzg.mw.tum.de.*

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