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Alternative microstructures and their influence on mechanical properties of case-hardened gears

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Abstract Case hardening is one of the most common heat treatment processes for highly loaded shafts and gears. Due to numerous investigations, a microstructure consisting of martensite with retained austenite (less than 30%) represents a high sustainable microstructure.

Besides this, there are some alternative microstructures compared to the commonly specified martensitic layer. The central question is how they influence the load carrying capacity of gears. A former research project was focused on the mechanical properties of carbonitrided parts by varying the amount of retained austenite. The investigations revealed that a microstructure containing a significantly increased amount of retained austenite can increase the flank load carrying capacity in comparison to standard case carburized gears. The tooth root bending strength was not influenced in a negative way.

A microstructure containing an increased amount of retained austenite can also be reached by gas carburizing. Furthermore, a variant containing bainite in the case hardened layer was adjusted. In an actual research project, the influence on the load carrying capacity of gears made out of the material 20MnCr5 was investigated in experimental test-runs, using spur gears. The results of the variants with alternative microstructure show some differences, e. g. in the hardness profiles, compared to results of standard case hardened gears. In comparison to the case hardened reference, the flank load capacity of the gears with the alternative microstructures showed increased flank load capacity numbers, whereas the tooth root bending fatigue was not influenced in a negative way.

1 Introduction

Highly loaded shafts and gears are commonly case hardened by gas carburizing and subsequently hardening with the aim to fulfil the high requirements. A microstructure consisting of martensite and retained austenite turned out as highly sustainable. Corresponding recommendations can also be found in gear standards such as ISO 6336 [6] and AGMA 2101 [1]. In the past, the research work concerning heat treatment was focused on the optimization of the heat treatment process of carburizing to achieve a fine martensitic microstructure with limited content of retained austenite. Due to these efforts, the recommendations according to ISO 6336 [6] can purposefully be achieved and the scatter in the carrying capacity results was further reduced. But no increase of the carrying capacity was obtained. By thermochemical heat treatment processes it is possible to modify the microstructure specifically. In this way, a further adjustment of the microstructure/properties of the components to the requirements could be possible and achieve possibly potentials to increase the carrying capacity. The results presented in this paper originate from a research project which was processed by FZG (TU Munich) and IWT (Bremen). At IWT the investigations concerning heat treatment and the study of microstructure took place, whereas at FZG, the load carrying capacity of gears was determined.

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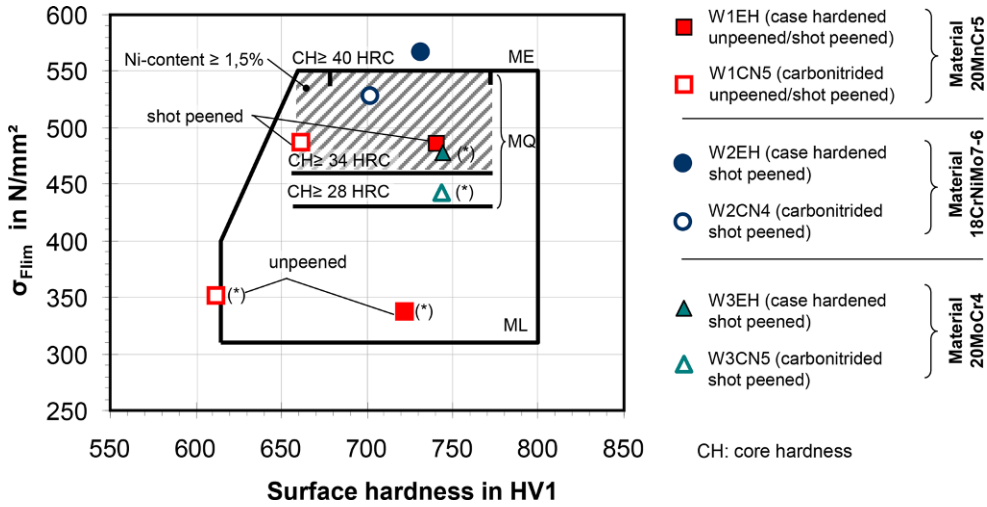

Fig. 1 Classification of the determined allowable bending stress numbers of carbonitrided gears with increased amount of retained austenite in the specifications of ISO 6336 for case hardened gears [8] (*reduced data points)

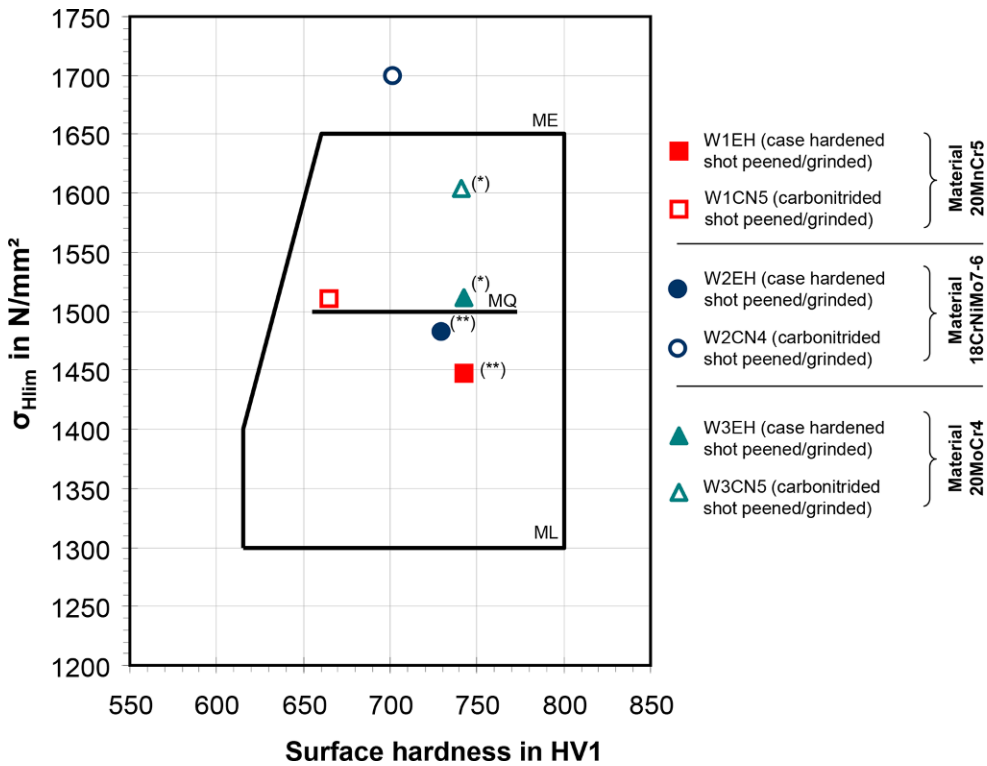

Fig. 2 Classification of the determined allowable contact stress numbers for carbonitrided gears with increased amount of retained austenite in the specifications of ISO 6336 for case hardened gears [8] (*reduced data points, **comparison and good correlation with results from earlier investigations [7, 9])

2 State of the art

On the basis of numerous investigations (e. g [9] and [12]). a martensitic layer with retained austenite (maximum amount of ~30%) turned out to be necessary to achieve high load carrying capacities. The results are also taken into account in gear standards such as ISO 6336 [6] or AGMA 2101 [1]. In recent investigations, the influence of an increased amount of retained austenite on the load carrying capacity of gears was investigated [8]. Therefore the amount of retained austenite was varied by the heat treatment process of carbonitriding. The investigations on the load carrying capacity (tooth root as well as tooth flank) were carried out on spur gears with the gear size module 5 mm made out of the materials 20MnCr5, 18CrNiMo7-6 and 20MoCr4. The results of the tooth root strength are shown in Fig. 1. Concerning the material 20MnCr5, it can be seen, that the endurance limit of the tooth root bending strength of the carbonitrided variants (amount of retained austenite ~60–70%) are generally speaking a little bit higher than the case hardened reference variant. This is shown in the unpeened as well as in the shot peened condition. The carbonitrided variants of the materials 18CrNiMo7-6 and 20MoCr4 (retained austenite content of ~55–65%)

Table 1 Chemical composition of the investigated batch of 20MnCr5

Element	C	Mo	Mn	Ni	S	P	Si	Cu
Weight %	0.20	0.05	1.22	0.24	0.002	0.004	0.38	0.07

Table 2 Main geometry of the test gears

Geometry			Test gears	
Parameter	Symbol	Unit	Pitting	Tooth root
Normal module	m_n	mm	5	5
Center distance	a	mm	91.5	–
Face width	b	mm	10	30
Number of teeth	z_1/z_2	–	17/18	24
Normal pressure angle	α_n	°	20	
Helix angle	β	°	0	
Profile shift coefficient	x/m_n	–	0.475/0.445	0.486
Tip diameter	d_a	mm	99.75/104.45	133.6

Table 3 Investigated variants

Variant	Symbol	Heat treatment
Reference	R	Gas carburizing
50% retained austenite	A	Gas carburizing
30% bainite	B	Gas carburizing

show a slight decrease in the tooth root endurance limit compared to the corresponding case hardened reference variants. Concerning the case hardened reference variant made out of the material 18CrNiMo7-6, it has to be taken into account, that the endurance limit value is very high and even exceeds the characteristic value of the material quality ME according to ISO 6336. All in all, the allowable bending stress numbers of all variants are typical for gears in the unpeened/shot peened condition. Additionally the pitting carrying capacity was investigated. The results are plotted in Fig. 2. It can be seen, that all variants in the carbonitrided state (retained austenite content of ~60%) show higher pitting endurance limits in comparison to the corresponding case hardened reference variants. The highest load carrying number was achieved by carbonitrided variant made out of the material 18CrNiMo7-6.

The results show that with carbonitrided gears with an increased amount of retained austenite potentials concerning the pitting load carrying capacity can be achieved compared to the case hardened reference. Furthermore, the tooth root endurance limits were not significantly reduced.

Additionally for bearings, a positive effect on the load carrying capacity was detected by the combination of bainitic microstructures with martensitic microstructures [2] and [3].

3 Aim of the investigation

The results summarized in the previous section show that alternative microstructures have the potential of a further increase of the load carrying capacity of gears. Within an actual research project [5], microstructures which purposely deviate from the recommendations of the gear standards were investigated in comparison to a microstructure which fulfils the recommendations. An increased amount of retained austenite (in this case 50%) was achieved by gas carburizing. Furthermore, a variant with 30% of bainite in the case hardened layer was adjusted.

4 Test gears and investigated variants

For the investigation of the tooth root bending fatigue as well as for the pitting load capacity, spur gears with a gear size of module 5 mm are used. All test gears were made out of one batch of the material 20MnCr5 (chemical composition in Table 1).

The main geometry data of the test gears are documented in Table 2. The test gears for the tooth bending fatigue are investigated in the unground condition whereas the tooth flanks of the test gears for the pitting tests were ground. All test gears were mechanical cleaned after the heat treatment process. The identification of the investigated variants is shown in Table 3.

All gears were gas carburized. To achieve the different microstructures in the surface layer, the heat treatment process was adjusted by varying the process parameters such as C-level or temperature control. Detailed information about each heat treatment process is documented in [5].

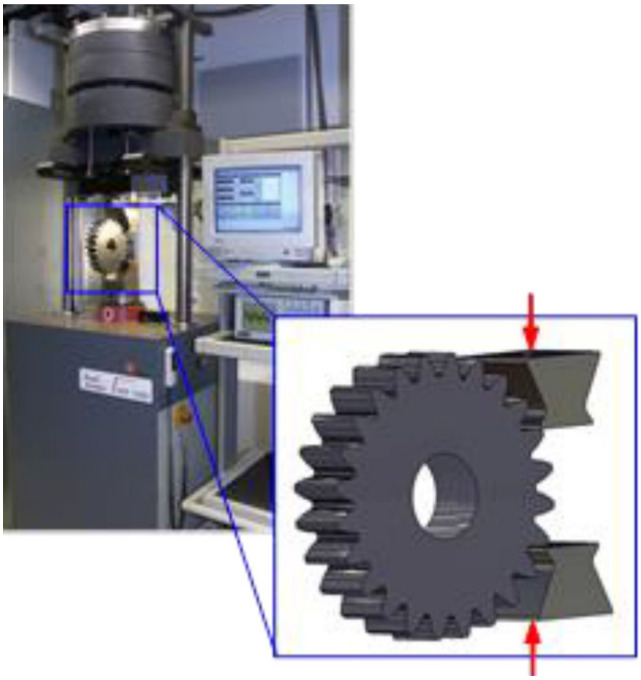

Fig. 3 Electro-magnetic pulsating test rig for the determination of the tooth bending strength

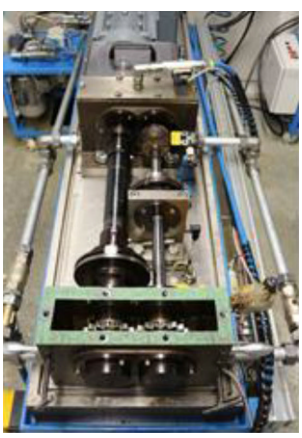

Fig. 4 FZG back-to-back test rig (a = 91.5 mm) used for investigations of the tooth flank

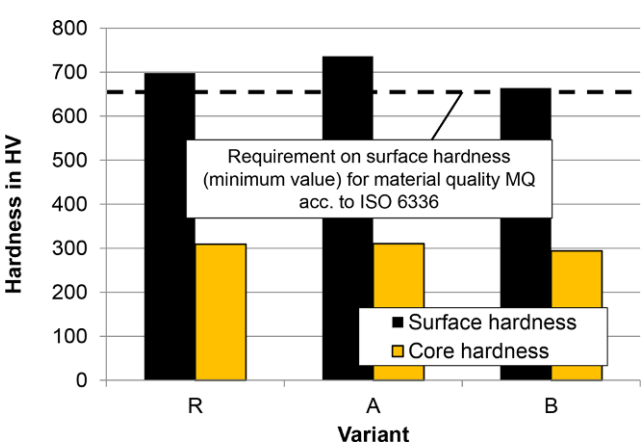

Fig. 5 Surface and core hardness values (mean values), determined in the tooth root of unground pulsator test gears

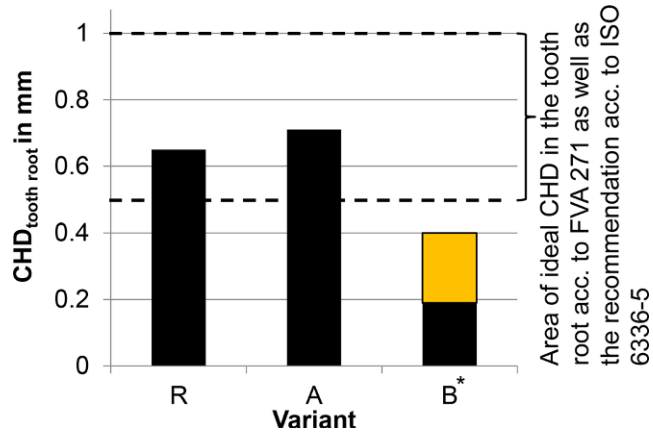

Fig. 6 Case hardening depth (CHD, mean values), determined in the tooth root of unground pulsator test gears (*for variant B the minimum and maximum values are plotted)

5 Test rigs and test conditions

The bending fatigue tests were carried out by means of an electro-magnetic pulsating test rig as shown in Fig. 3. The test rig consists of a machine frame, which incorporates test device, load cell and test gear. The pulsating load is generated by a dynamic actuator, which is connected to a dynamic spring by the exciting magnet, which is directly connected with the pulsating cross beam by two rod springs. The test gears were symmetrically clamped and tested over 4 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 which was always lower than 10% of the test load. The test runs were stopped after $6 \cdot 10^6$ load cycles. The test runs for the determination of surface durability (pitting) were performed on FZG back-to-back gear test rigs with a centre distance of a = 91.5 mm. Fig. 4 shows a picture of the test rig with a centre distance of 91.5 mm. The test rig is driven by a three-phase asynchronous engine with a constant speed of 3000 rpm. Test pinion and test gear are mounted on two parallel shafts which are connected to a drive gear stage with the same gear ratio. The shaft of the test pinion consists of two separate parts which are connected by a load clutch. A defined static torque is applied by twisting the load clutch using defined weights on the load lever or by twisting the load clutch with a bracing device. The torque can be controlled indirectly at the torque measuring clutch as a twist of the torsion shaft. The engine only has to provide the power loss of the two gear boxes in this closed power loop. For the tests described herein, the pinion was mounted on the torsion shaft and

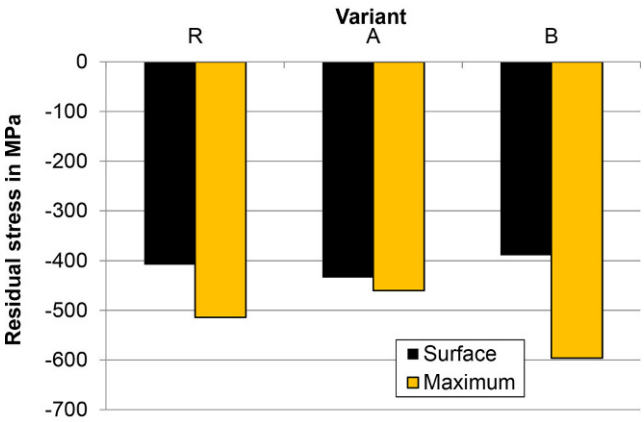

Fig. 7 Residual stresses, measured by X-ray diffraction in the tooth root section of the pulsator test gears on the surface and maximum value

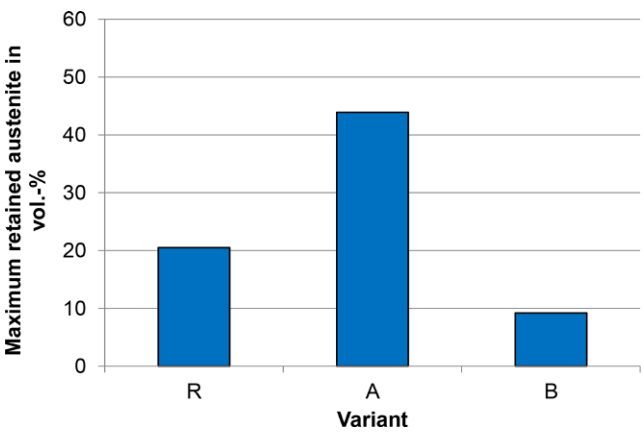

Fig. 8 Retained austenite (maximum value), measured by X-ray diffraction in the tooth root section of the pulsator test gears

had the same speed as the engine. The load was applied in a way that the pinion was the driving gear and the gear was driven. All test runs were performed with FVA-reference oil FVA3A [4] under oil spray lubrication (approx. 2 l/min into the tooth mesh) with $\vartheta_{Oil} = 60\,°C$ (±2 °C). The test runs were stopped after $50 \cdot 10^6$ load cycles.

6 Hardness, microstructure and residual stresses of test gears after heat treatment

In the following sections, the results of the experimental investigations are presented. In order to characterize the different heat treatment batches, various investigations took place. The values were determined on gears for tooth root bending as well as on gears for the pitting investigations for each heat treatment batch.

6.1 Test gears for tooth root bending

In Fig. 5 the measured surface hardness values (mean value of left and right tooth root) are compared. The values were determined in the tooth root section of the unground pulsator test gears. It can be seen, that variant A shows the highest surface hardness value and variant B the lowest one. Furthermore, the recommendation for the minimum surface hardness value (660 HV1) according to ISO 6336 [4] is added. All variants fulfil this recommendation. Additionally, the core hardness values are presented. All variants show nearly identical core hardness values. The determined CHD values (mean value of right and left tooth root, except variant B) are compared in Fig. 6. Variant A shows the highest CHD. Regarding variant B, it has to be mentioned, that the hardness profile shows a large scatter. Therefore for variant B the minimum and maximum value of the CHD is presented. The recommendation according to ISO 6336 [6] and the optimal CHD according to [10] and [11] is added. Variant R and A fulfil the re-commendation, the values of variant B are smaller.

The measured residual stresses (Fig. 7) prove that all variants have compressive residual stresses on the surface. Furthermore, the maximum of the compressive residual stress state was determined and is also compared in Fig. 7. Variant A shows the highest residual stresses on the surface and the lowest maximum value. Variant B shows the opposite, the surface residual stresses are the lowest, but this variant has the highest maximum value. In total, all values are in a typical range for mechanical cleaned gears. In Fig. 8, the measured amount of retained austenite is

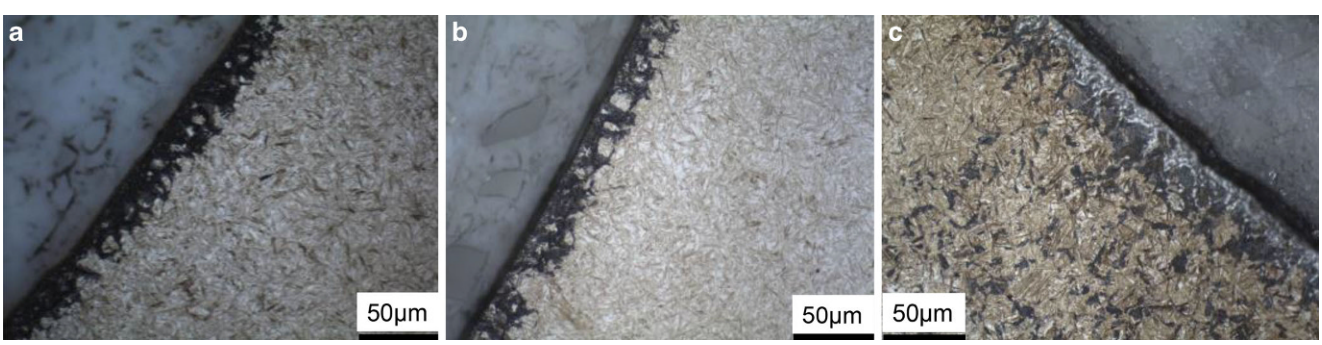

Fig. 9 Microstructures of variants R (**a**), A (**b**) and B (**c**), recorded in the tooth root section

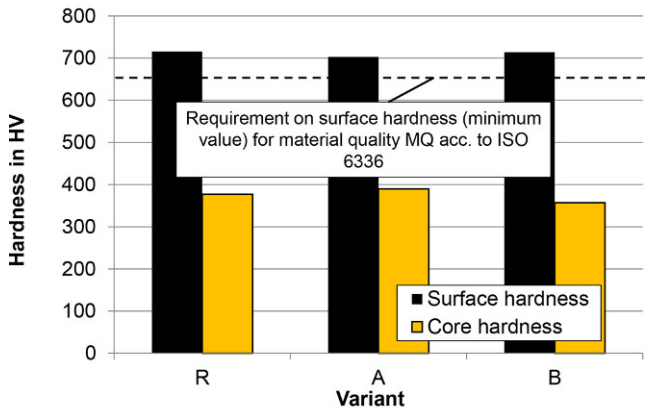

Fig. 10 Surface and core hardness values (mean values), determined on the tooth flank of ground test gears

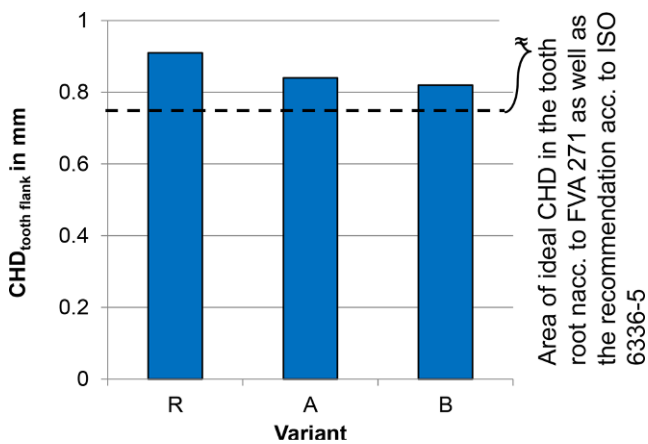

Fig. 11 Case hardening depth (CHD, mean values), determined on the tooth flank of ground test gears

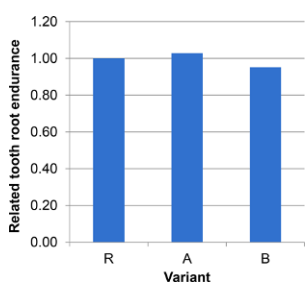

Fig. 12 Comparison of the related endurance limit values of the tooth root bending

presented. With 20% retained austenite variant R fulfils the recommendations of ISO 6336 [6] and AGMA 2101 [1]. Variant A achieved with about 45% retained austenite nearly the specification of 50% retained austenite. The lowest amount of retained austenite was determined for variant B. In Fig. 9, the microstructures of variants R, A and B are exemplarily shown, recorded in the tooth root section. All variants consist of a martensitic microstructure with retained austenite and a non-martensitic layer on the surface. Variant A contains an increased amount of retained austenite. Furthermore, variant B shows areas with increased amount of bainite/troostite. Due to this fact, the scatter in the hardness profile and the different CHD values of variant B can be explained.

6.2 Test gears for pitting investigations

In Fig. 10 the measured surface hardness values (mean value of left and right tooth flank) are compared. The values were determined on the tooth flank of the ground test gears. It can be seen, that all variants show nearly identical surface hardness values. Furthermore, the re-commendation for the minimum surface hardness value (660 HV1) according to ISO 6336 [6] is added. All variants fulfil this recommendation. Additionally, the core hardness values are presented. All variants show comparable core hardness values. The determined CHD (mean value of right and left tooth flank) is compared in Fig. 11. Variant R shows the highest CHD. Concerning variant B, the hardness profile does not show such great scatter like the ones for the pulsator test gears. The recommendation according to ISO 6336 [6] and the optimal CHD according to [10] and [11] is added. All variants have typical CHD-values for the investigated gear size.

7 Results and discussion of the load carrying capacity investigations

7.1 Tooth root bending

For the determination of the endurance limit of the tooth root bending strength of each variant, about 10–12 test runs were performed. In Fig. 12 the related endurance limits of all three variants are plotted. In this case, the endurance limit values are related to the value of the reference variant R. Variant A shows a slightly higher value, variant B a slightly lower one than the reference variant. The differences of the endurance limit values are in total less than 5% related to the case hardened reference. All in all, the results show that alternative microstructures do not have a significantly negative influence on the endurance limit values of the tooth root bending compared to the case hardened reference variant. But it has to be taken into account that all variants were tested in the mechanical cleaned condition. By mechanical cleaning other effects/influence factors like different CHD values could be covered.

7.2 Pitting load capacity

Additionally, the pitting load carrying capacity of all variants was compared. The test runs were performed on two load stages (Fig. 13). Load stage one (nominal contact stress σ_{H0} = 1700 N/mm^2) was specified in the way that the refer-

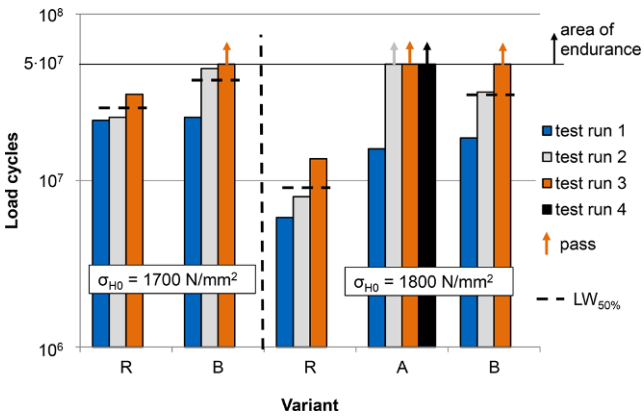

Fig. 13 Comparison of the test runs for pitting

ence variant R fails due to pitting after about $30 \cdot 10^6$ load cycles. For load stage two (nominal contact stress σ_{H0} = 1800 N/mm²), the load was increased so far that reference variant R fails due to pitting after about $10 \cdot 10^6$ load cycles. Due to the fact that variant A reached three times the herein defined max. running time of $50 \cdot 10^6$ load cycles on load stage two without any damage, it was renounced to test load stage one. Variant B was investigated on both load stages. Additionally the averaged numbers of load cycles $LW_{50\%}$ (failure probability 50%) are shown in Fig. 13, except for variant A due to the three run outs. Both variants A and B show a higher pitting load capacity compared to the case hardened reference variant R. Variant A shows the highest potential concerning pitting load carrying capacity. The test gears of the single early failure of variant A were further inspected. The metallographic investigations did not show any difference compared to the test gears which reached $50 \cdot 10^6$ load cycles without any damage. The metallographic investigations of the gears of variant B did not show inhomogeneities like the gears used for the determination of the tooth root bending strength.

8 Conclusion

This paper dealt with the influence of alternative microstructures on the load carrying capacity of case hardened gears. It was shown that the aspired microstructures could be set, but the heat treatment processes are not trivial. The test-accompanying investigations show a variety of different characteristic values. The flank load capacity of the gears with the alternative microstructures showed a significantly increased pitting load carrying capacity number in comparison to the case hardened reference. The tooth root bending fatigue, by contrast, was not influenced in a negative way. All in all, the results of the prior investigation 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 but may even have a great potential to increase especially the contact (pitting) fatigue strength.

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