Deep nitriding—contact and bending strength of gears with increased nitriding hardening depth

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Abstract

The load carrying capacity of gears can be significantly increased by nitriding. However, the required nitriding hardening depth depends on the stress level and the gear size. In order to achive a high fatigue resistance and durability of nitrided gears an adequate nitriding hardening depth is necessary. In industrial practice, a nitriding hardening depth (NHD) of about 0.6 mm is currently regarded as the upper limit that can be reached within a reasonable time and cost. This also limits of the load carrying capacity of nitrided gears, in particular with increasing gear sizes. Therefore, case hardening is the main treatment used with increasing gear sizes, although nitriding provides some advantages over case hardening. However, with an increased nitriding hardening depth, a significant increase in the load carrying capacity of nitrided gears for medium and larger gear sizes could be expected, which will be discussed in this publication. In order to evaluate the expected potential of the load carrying capacity of nitrided gears with an increased nitriding hardening depth of NHD $\approx$ 0.8 to 1.0 mm (deep nitriding heat treatment) made out of the materials 31CrMoV9 (1.8519), 30CrNiMo8 (1.6580) and 32CDV13 (alloy for aerospace applications according to AIR 9160), experimental investigations were carried out, which will be discussed in this publication. Both, the tooth root bending strength and the flank load carrying capacity were investigated.

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Tiefnitrieren – Zahnflanken- und Zahnfußtragfähigkeit von Zahnrädern mit erhöhter Nitrierhärtetiefe

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Zusammenfassung

Durch Nitrieren kann die Beanspruchbarkeit von Zahnrädern hinsichtlich der Zahnflanken- und Zahnfußtragfähigkeit signifikant gesteigert werden. Die Dauerfestigkeit und damit die Lebensdauer nitrierter Bauteile steigen mit zunehmender Nitriertiefe, wobei die benötigte Nitriertiefe abhängig von der Baugröße der Verzahnung ist. In der Praxis wird eine Nitrierhärtetiefe (NHD) von etwa 0,6 mm als Grenzwert angesehen, die mit vertretbarem Zeit- und Kostenaufwand erreicht werden kann, so dass mit zunehmender Baugröße der Verzahnung überwiegend das Einsatzhärten Anwendung findet. Beim Tiefnitrieren werden Nitrierhärtetiefen von etwa 0,8 – 1,0 mm angestrebt, daher ist durch diese Behandlung eine deutliche Steigerung der Belastbarkeit der nitrierten Zahnräder bei mittlerer und größerer Baugröße zu erwarten. Um das erwartete Tragfähigkeitspotenzial von nitrierten Zahnrädern mit erhöhter Nitrierhärtetiefe von NHD ≈ 0,8 bis 1,0 mm (Tiefnitrieren) aus den Werkstoffen 31CrMoV9 (1.8519), 30CrNiMo8 (1.6580) und 32CDV13 (Legierung für Luftfahrtanwendungen gemäß AIR 9160) zu bewerten, wurden experimentelle Untersuchungen zur Zahnflanken- und Zahnfußtragfähigkeit durchgeführt.

1 Introduction

In addition to case hardening, nitriding is an important heat treatment option for increasing the load carrying capacity of highly loaded gears by means of surface hardening. In some cases, nitrided gears are comparable to or even exceed case hardened gears in terms of contact and bending strength. Generally, nitrided gears are characterized by a thin but very hard compound layer of iron and alloy element nitrides directly on the surface. The thickness of the compound layer is only a few micrometers, followed by a diffusion layer which reaches more deeply into the material. Nitrided gears are especially resistant to scuffing, wear and corrosion and due to their increased heat resistance are also suitable for the use at higher operating temperatures [1]. Since no phase transformation takes place in the material during nitriding, nitrided gears are characterized by low distortion, which is a significant advantage over the classic case hardening process. For this reason, depending on the application, grinding after nitriding is usually not necessary. As a result, nitriding offers potential for cost savings in gear manufacturing. Nevertheless, in comparison with case hardened gears, the level of knowledge about nitriding gears is more limited.

2 Motivation and research objects

In addition to the current gear standard ISO 6336-5 [2] and the strength numbers specified therein for the tooth root and tooth flank fatigue strength, individual investigations have been carried out on nitrided gears over the past 55 years. In some cases, the results of these tests indicate high load carrying capacity numbers in comparison to case hardened gears. The reported test results were mainly determined on test gears with nitriding hardening depths selected as a function of the test gear size, taking into account the recommendations for an adequate nitriding hardening depth of the gear standard ISO 6336-5 [2]. Consequently, the NHD of the gears is limited to a range of 0.1 to 0.6 mm [3–10].

Higher nitriding hardening depths (NHD >0.6 mm) have not yet been systematically investigated. For this reason, knowledge about the load carrying capacity of nitrided gears with a NHD greater than 0.6 mm is still limited, which means further research on this topic is needed. However, with an increased nitriding hardening depth, a significant increase in the load carrying capacity of nitrided gears for medium and larger gear sizes could be expected, which will be discussed in this publication. In order to evaluate the expected potential of the load carrying capacity of ni-

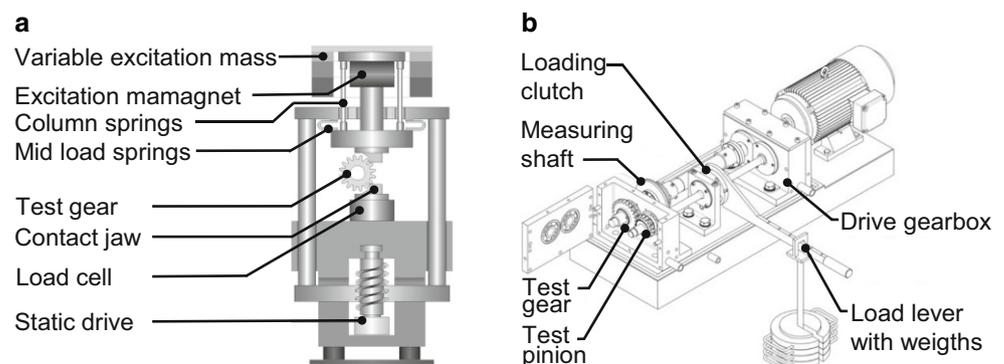**Fig. 1** Test rigs (schematically) [8]. **a** Pulsator test rig. **b** FZG back-to-back test rig, a = 91.5 mm

a
Variable excitation mass
Excitation mamagnet
Column springs
Mid load springs
Test gear
Contact jaw
Load cell
Static drive

b
Loading clutch
Measuring shaft
Test gear
Test pinion
Drive gearbox
Load lever with weigths

Table 1 Main geometry data of the test gears

Parameter	Symbol	Unit	Test gear	
			Flank load carrying capacity	Tooth root bending strength
Normal module	m_n	mm	5	
Center distance	a	mm	91.5	–
Number of teeth	z_1/z_2	–	17/18	24
Face width	b	mm	14	30
Normal pressure angle	α_n	°	20	
Helix angle	β	°	0	

Table 2 Test variants (NHD_{400HV}: Nitriding hardness depth, determined at a hardness limit of 400 HV acc. to ISO 6336-5 [2] and K_N: Nitriding potential)

Variant	NHD_{400HV} in mm	Two-stage nitriding	Application of grinding
30CrNiMo8	0.8 to 1.0	520 °C 15 h $K_N = 1$	Before nitriding
31CrMoV9	Large gearbox application	530 °C 170 h $K_N = 0.5$	
32CDV13	0.8 to 1.2	520 °C 15 h $K_N = 1$	
	Aviation application	570 °C 130 h $K_N = 0.5$	

trided gears with an increased nitriding hardening depth of NHD ≈ 0.8 to 1.0 mm (deep nitriding heat treatment) made out of the materials 31CrMoV9 (1.8519), 30CrNiMo8 (1.6580) and 32CDV13 (alloy for aerospace applications according to AIR 9160), experimental investigations were carried out as part of the research project FVA 615 II [8] (IGF 17321 N), on which this publication is mainly based. Both the tooth root bending strength and the flank load carrying capacity were investigated.

3 Methods and materials

This section describes the test setup for the experimental investigations of the tooth root and flank load carrying capacity as well as the test gears and test variants. The tests are based on the requirements of ISO 6336-5 [2] for gears of material quality MQ and on the specifications of FVA guideline 563 I [11].

3.1 Test rigs

As part of the research project [8], experimental investigations were carried out on the tooth root and the flank load capacity. The tooth root bending strength tests were performed on electromagnetic pulsator test rigs as shown in Fig. 1a. The test gears were fixed symmetrically between two jaws. A special tool was used to adjust the exact position of the test gear. Flank angle deviations were compensated by means of detailed adjustment, so that a uniform load distribution over the face width of the entire tooth can be assumed [1].

The experimental investigations for the flank load carrying capacity were carried out on a FZG back-to-back gear test rig [8] with a center distance of a = 91.5 mm, as shown schematically in Fig. 1b. 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. A three-phase asynchronous engine drives the test rig [10, 12, 13].

3.2 Test gears and test variants

The main geometry data of the test gears are shown in Table 1. The experimental investigation of the load carrying capacity was carried out on three variants as listed in Table 2. Furthermore, Table 2 shows the targeted NHD, as well as the specifications of the heat treatment and the machining condition of the test gears. The test gears were extensively characterized by means of destructive and non-destructive measuring methods. This included, for example, a 2- and 3-dimensional surface measurement, metallographic examinations of the surface layer and the core material, as well as documentation of the hardening profile.

Before nitriding, all the test gears investigated in the test runs were ground with a short tip relief of $C_a = 40\,\mu m$ on the pinion and wheel in order to avoid a reduction in the gear quality and subsequent dynamic effects. The application of a grinding process for each test gear ensured the required gear quality ($Q \le 5$) and flank surface roughness ($Ra \le 0.30\,\mu m$). In order to compensate the expected edge bulges after nitriding, the pinion and wheel were also corrected with an end relief on both sides, with a maximum amount of 45 μm each at the edge of the flank over a width of approx. 3.5 mm. The necessary gear tooth modifications were determined in preliminary tests.

3.2.1 Chemical analysis

The chemical composition of the three materials investigated was determined on the nitrided gear (core material) in the spark spectrometer. The values determined are in accordance with the specifications of the DIN EN ISO [14, 15] and show no further anomalies.
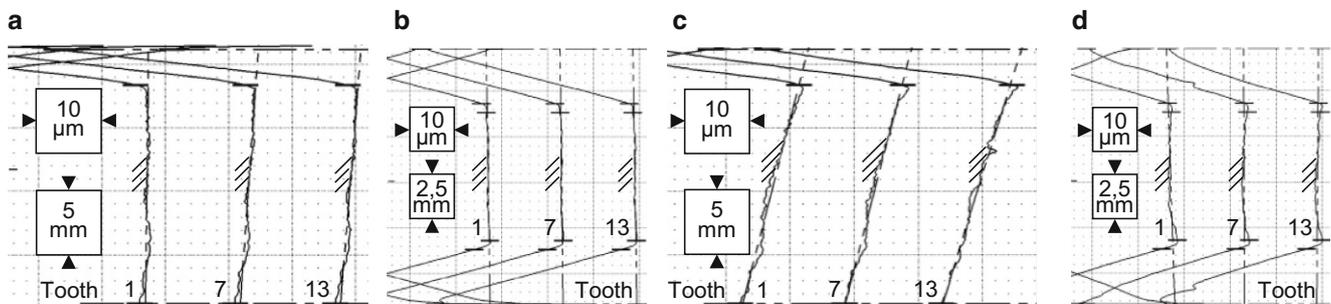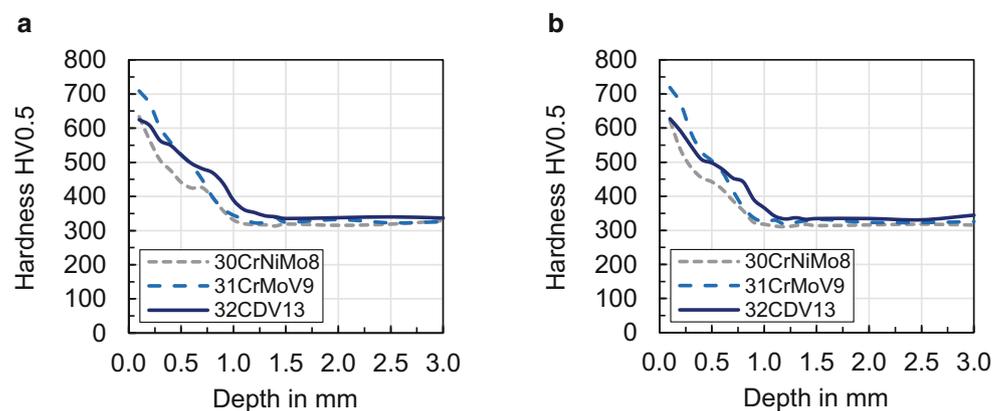
Fig. 2 Comparison of the profile (**a**, **c**) and flank lines (**b**, **d**) of a pinion ground before nitriding with tip and endrelief. **a**, **b** Before nitriding. **c**, **d** After nitriding

Fig. 3 Hardness depth profiles of the test gears, average values of left and right tooth flank respectively right and left tooth root fillet. **a** Tooth flank (pitch circle diameter). **b** Tooth root fillet (30° tangent)

3.2.2 Gear quality

All running test gears investigated were uniformly measured before (Fig. 2a and b) and after the nitriding treatment (Fig. 2c and d) with regard to gear quality, in accordance with DIN 3962 [16] (profile line, flank line, pitch) in each case on three teeth evenly distributed over the circumference on a Klingelnberg P40 3D coordinate measuring system. In addition, the gears of all the variants examined, which were used for the investigations of the tooth root load capacity, were evaluated in terms of the gear quality. The respective measurement records show a comparable quality of the test gears for each test gear geometry, which, with the exception of the face profile angle deviation of the nitrided gear teeth, correspond to the specifications and the required gear qualities (gear quality $Q \leq 7$ for the investigation of the tooth root bending strength or $Q \leq 5$ for the investigation of the flank load carrying capacity). The measurements taken after nitriding treatment, as illustrated in Fig. 2c and d, show that the long nitriding times negatively affect the profile angle and lead to deviations from the desired tooth quality. In addition, it can be determined that despite tooth flank corrections, slight edge bulges are present in the transition area of the active tooth flank to the tip relief or to the end relief on both sides, which, however, should not lead to any significant meshing disturbances in the running test due to their low extent.

The surface topography of all running test gears was measured with a Hommel T8000 electrical scanning device using the surface scanning method. The measurement was carried out in the profile direction and using a phase-corrected high-pass filter in accordance with DIN EN ISO 11562 [17]. After nitriding, the arithmetic mean flank roughness Ra of the variants has been determined in the range of 0.28 to 0.42 μm. In order to improve the flank topography and avoid micropitting as far as possible, a one-stage run-in has been applied to all variants (Torque at pinion $T_1 = 135\,\text{Nm}$, pinion speed $n_1 = 2250\,\text{rpm}$, FVA 3A (ISO VG 100) acc. to [18], oil temperature $\vartheta_{Oil} = 60\,°\text{C}$, number of load cycles $N = 260 \bullet 10^3$). After the run-in procedure, a comparable flank surface roughness of 0.15 to 0.25 μm has been measured on all variants. In addition, the surface topography in the area of the tooth root fillet was determined on one pulsator test gear per variant for the evaluation of the pulsator results. The measurement results of the three investigated variants are largely comparable and were averaged, showing a value of Rz = 5.1 μm.

3.2.3 Hardening depth profiles

Metallographic investigations were carried out to determine the hardening depth profile on the cross-section of each variant. The measuring points were set uniformly at the

Table 3 Metallographically determined material properties in the tooth root and tooth flank area (mean values)

Variant		NHD_{400HV} in mm acc. to ISO 6336-5 [2]	Surface hardness HV0.5	Core hardness HV0.5
30CrNiMo8	Tooth flank	0.79	634	311
	Tooth root	0.67	622	
31CrMoV9	Tooth flank	0.78	709	309
	Tooth root	0.74	719	
32CDV13	Tooth flank	0.98	625	337
	Tooth root	0.88	628	

level of the pitch circle and in the area of the 30° tangent to the tooth root fillet normal to the component depth on both sides of the tooth flank. In Fig. 3, the results of the Vickers hardness measurements in the tooth flank and root areas are summarized redundant for all three investigated deep nitrided test gear variants investigated. To determine the nitriding hardening depth, a hardness of 400 HV0.5 was defined as the limit value in accordance with ISO 6336-5 [2]. Depending on the nitriding treatment used, the test variants investigated here show different hardness depth profiles both on the tooth flanks (at the level of the pitch circle diameter) and in the root fillet in the area of the 30° tan-

gent. The comparable core hardness of the three variants is independent of the nitriding treatment and is within the usual range of quenched and tempered materials.

However, there are clear differences in the hardness characteristics near the surface. The surface hardness values determined for 30CrNiMo8 and 32CDV13 are in a comparable range despite the different nitriding treatments and are approx. 620 to 630 HV0.5. For the material 31CrMoV9, a significantly higher surface hardness (approx. 709 to 719 HV0.5) was determined on the tooth flank and in the tooth root fillet (30° tangent). It should be noted that for technical reasons the surface hardness values shown here were not determined in, but just below the compound layer. The core hardness of 30CrNiMo8 (approx. 311 HV0.5) and 31CrMoV9 (approx. 309 HV0.5) are almost identical. In contrast, a slightly higher core hardness of approx. 337 HV0.5 was determined for 32CDV13. A summary of the metallographically determined material properties (mean values) of the variants investigated is shown in Table 3.

3.2.4 Microstructural condition

Exemplary etched metallographic cross sections per test gear variant are shown in Fig. 4. The test gears show a uniformly structured diffusion layer with quenched and tempered structure, which is uniformly thick in the tooth tip, tooth flank and tooth root areas. With the exception of the 30CrNiMo8 variant, the materials do not show any

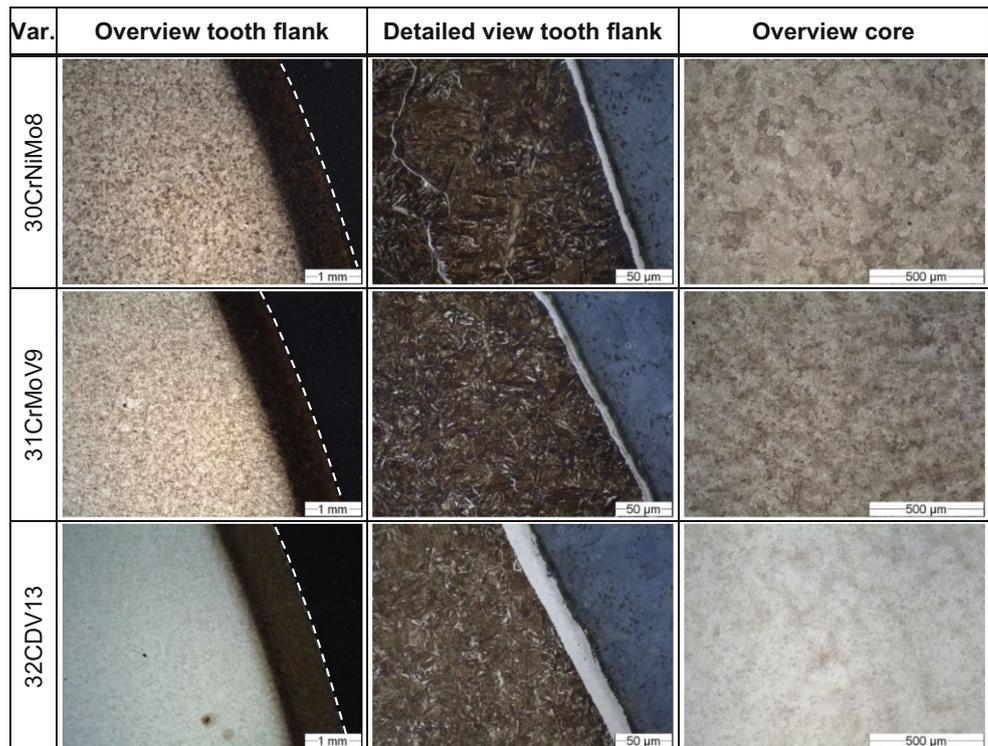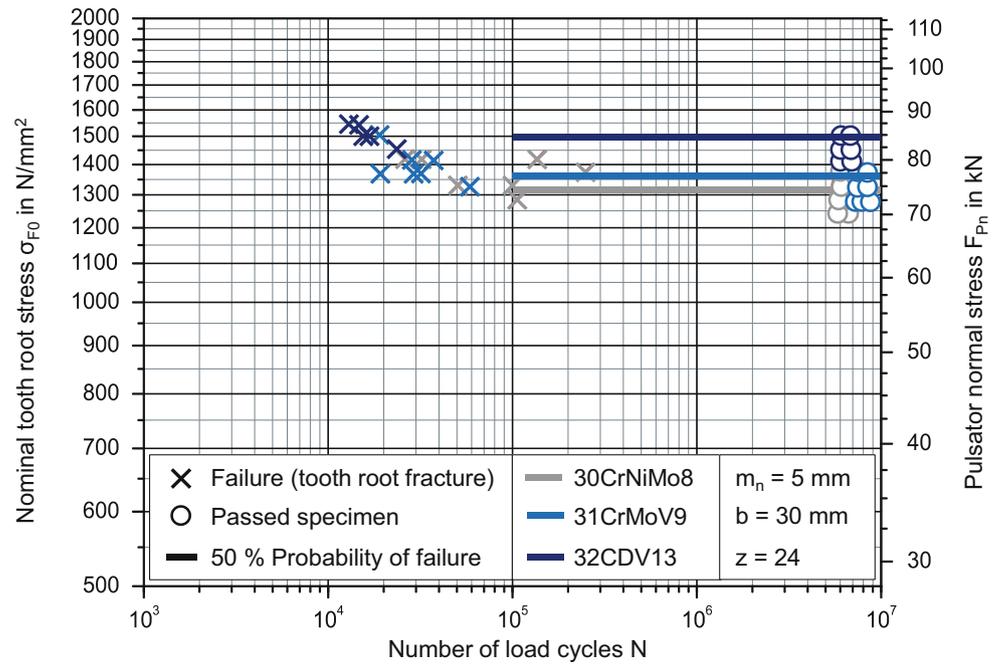**Fig. 4** Exemplary metallographic cross sections of the test gears

Fig. 5 Results of the pulsator tests on the tooth root bending strength

visible grain boundary nitride network within the diffusion layer. The present compound layers (white layers) of the different material variants vary in thickness depending on the nitriding treatment applied. Compared with the thinner compound layer thickness of approx. 8 μm of the 30CrNiMo8 and 31CrMoV9 variants, the 32CDV13 variant shows a thicker compound layer of approx. 20 μm due to the higher nitriding treatment temperature. In all cases, the compound layers are uniformly and continuously shaped over the tooth profile and show no visible cracks or other damages. The formation of porous seam can be classified as low in all three variants. The quenched and tempered core structure following the diffusion layer is comparable in all three variants investigated, with the 30CrNiMo8 characterized by a comparably slightly larger grain structure. The microstructures of all the variants investigated here correspond to the state of the-art/industrial practice and show no other anomalies.

4 Results and discussion

4.1 Tooth root bending strength

The tooth root bending strength of the deep nitrided gears has been uniformly investigated in the pulsator test rig. The fatigue strength tests carried out showed that some failures have already occurred due to tooth root fracture in relatively low numbers of load cycles. Therefore, based on test experience, no explicit tests were undertaken in the area of finite life fatigue strength but tests were focused on the range of long (infinite) life. Fig. 5 shows the experimental determined tooth root bending strength (single test points and evaluated endurance strength for 50% failure probability).

The results show that the tooth root fractures that occurred for all variants occur primarily in the area of relatively low numbers of load cycles. A high overload sensitivity of nitrided gears is also reported from past investigations [4] and [6]. This indicates a relatively high overload sen-

Table 4 Comparison of the determined durable nominal tooth root stress numbers at 50% failure probability $\sigma_{F0,pulsator,\infty,50\%}$, the estimated nominal stress numbers at 1% failure probability $\sigma_{F lim}$ and the nominal stress numbers (bending) at 1% failure probability for nitrided nitriding and case hardened steels acc. to ISO 6336-5 [2]

Variant	$\sigma_{F0,pulsator,\infty,50\%}$ in N/mm²	$\sigma_{F lim}$ in N/mm²	Nominal stress numbers (bending) $\sigma_{F lim}$ in N/mm² acc. to ISO 6336-5 [2]		
			Material quality	Nitriding steels	Case hardened steels
30CrNiMo8	1322	490	MQ	420	500 [a]
31CrMoV9	1367	507	ME	468	525
32CDV13	1500	550			

[a] Core hardness ≥ 30 HRC (30 HRC corresponds to approx. 300 HV)

sitivity of the investigated gears. This must be taken into account when evaluating the determined tooth root bending strength of the investigated variants. Therefore, tests in the area of finite-life fatigue strength do not provide any additional benefit. In addition, the variant 30CrNiMo8 show a relatively high test scatter, which must be taken into account when converting the endurable nominal tooth root stress for 50% failure probability into a nominal stress number, e.g. according to ISO 6336-5 [2] (1% probability of failure). All fracture surfaces examined show no significant anomalies, e.g. no tooth root fractures with crack initiation below the surface of the gear.

Table 4 shows the results of the determined durable nominal tooth root stress numbers at 50% failure probability $\sigma_{F0,pulsator,\infty,50\%}$ and the estimated nominal stress numbers (bending) at 1% failure probability $\sigma_{F\,lim}$. Furthermore, Table 4 gives a comparative comparison of the estimated nominal stress numbers (bending) at 1% failure probability $\sigma_{F\,lim}$ with the stress numbers (bending) at 1% failure probability for nitrided nitriding and case hardened steels acc. to ISO 6336-5 [2].

The determined durable nominal tooth root stress numbers at 50% failure probability are in the medium (30CrNiMo8 and 31CrMoV9) or upper (32CDV13) strength range of case hardened, shot blasted gears of comparable size. Estimates of the nominal stress numbers at 1% failure probabililty acc. to ISO 6336-5 [2] ($\sigma_{F\,lim} \approx 490$ to $550\,N/mm^2$) are in the middle (30CrNiMo8 and 31CrMoV9) and upper (32CDV13) range of the strength numbers of case hardened, shot blasted gears of comparable size and clearly exceed the strength numbers for gas nitrided gears specified in the ISO 6336-5 [2] standard.

Despite lower surface hardness than the 30CrNiMo8 variant, the tooth root load carrying capacity of the 32CDV13 variant is approx. 10% higher compared to the 30CrNiMo8 and 31CrMoV9 variants. The determined value for the material 31CrMoV9 exceeds the values documented in the research projects [4] and [6]. In addition, a high overload sensitivity was also determined for the tested variants, which is already known from previous investigations of completed research projects [4] and [6]. This must be taken into account accordingly when using nitrided gears in practical applications.

4.2 Flank load carrying capacity

The flank load carrying capacity of deep nitrided gears has been investigated in the FZG back-to-back gear test rig with a center distance of $a = 91.5\,mm$. As only a limited number of test gears was available, a limited number of test runs in the range of the expected high and medium limited life was performed. Further tests are scheduled within a new project FVA 615 III [19]. All gear running tests were carried out with lubricants from the FVA reference oil catalog [18]. The reference oil FVA 3A (ISO VG 100) with an additive content of 4% by volume Anglamol 99 was used for the tests. All gear running tests were carried out using injection lubrication at an oil temperature of 60°C and a spray rate of approx. 2 liters per minute. The speed at the pinion has been constantly set to $n_1 = 3000\,rpm$. Due to the fact that the experimental investigations have been focused on the area of finite life fatigue strength, an explicit limiting number of load cycles has not been defined. Tests with no significant damage on the loaded tooth flank surface after

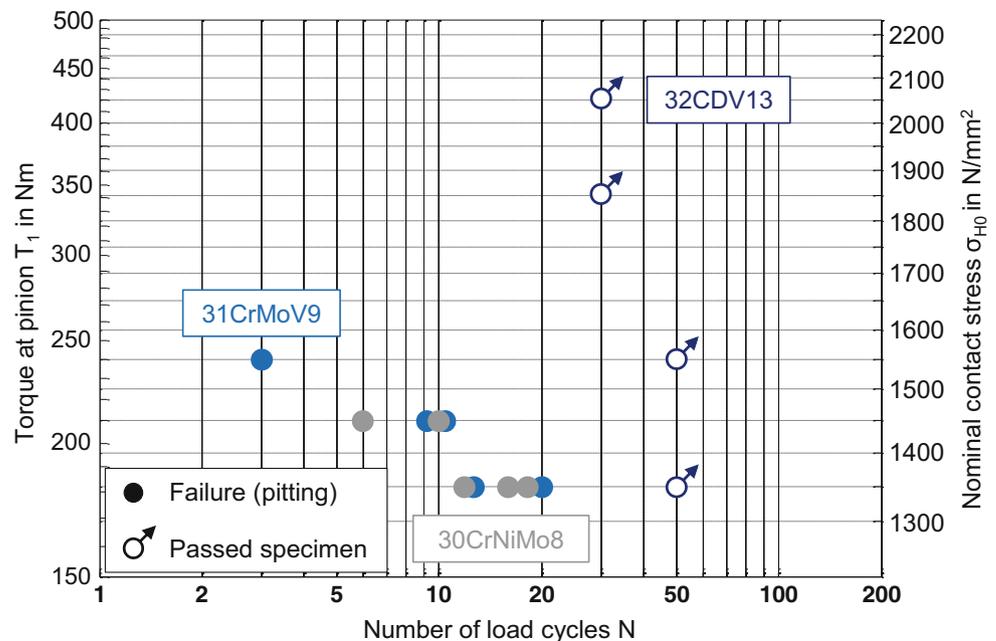**Fig. 6** Results of the running tests on the flank load carrying capacity

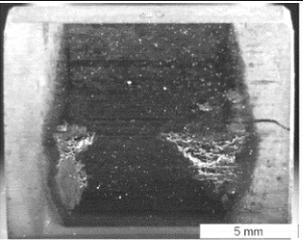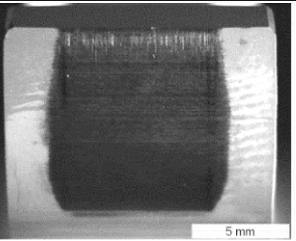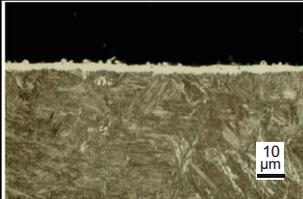**Fig. 7** Exemplary tooth flank pictures after the running tests

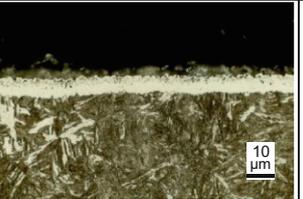**Fig. 8** Comparative representation of exemplary microsections of the tooth flank surface in new and tested condition
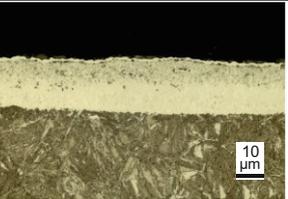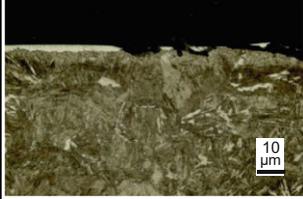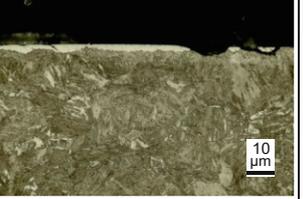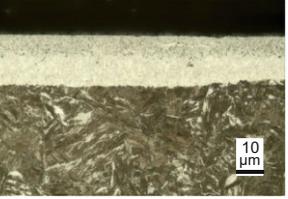
30 or 50 million load cycles respectively were stopped and counted as passed specimens. The results for the flank load carrying capacity are summarized in a Woehler diagram in Fig. 6.

The tooth flank condition and any tooth flank damage of the respective test gears were uniformly documented after the tooth flank load capacity tests. Fig. 7 shows exemplary tooth flank damages that occurred in the running tests and tooth flanks that show no significant changes on the tooth flank surface even after the limiting number of load cycles of 30 or 50 million load cycles were reached.

For each test variant, metallographic examinations were carried out on tested gears, with the focus of the examination on the microstructure near the surface, in particular the condition of the compound layer at the level of the pitch point of the tooth flank. Fig. 8 shows pictures of a damaged (30CrNiMo8, 31CrMoV9) and an intact (32CDV13) tooth flank surface, respectively, and the corresponding as-tested condition for comparison.

The microstructure images of the 30CrNiMo8 and 31CrMoV9 variants show that the pore seam present in the new condition is almost non-existent after testing. In addition, it can be seen that the compound layer is damaged and partially eroded. The material structure below the removed compound layer already shows the beginning indications of fractured microstructures, which can lead to corresponding pitting in the further progress. Due to the higher treatment temperature, the 32CDV13 variant shows a significantly thicker compound layer in new condition. In the tested condition, this compound layer shows no damage or significant changes after approx. 30 million load cycles and relatively high nominal contact stress number of $\sigma_{H0} = 2050\,N/mm^2$. As well as detection of a smoothing of the active flank surface, it is clear that the oxidic layer (thin, white layer above the pore seam) present in the new state was removed during the running test. A possible shrinkage or compression of the existing pore seam is not visible on the basis of the available microstructural images. To obtain indications of possible plastification of the com-

pound layer, the ultramicrohardness (UMH) measurement acc. to DIN EN ISO 14577 [20] was used to measure the hardness of the compound layer (below the pore seam) on material the 32CDV13 before and after the running test. At 1116 HV0.001 ($\pm$105 HV0.001) before the running test and 1130 HV0.001 ($\pm$57 HV0.001) after the running test, the difference in hardness of the compound layer is within the range of scatter of the measurement, so no significant difference can be detected.

The running tests reveal that the test variants investigated here show significantly different tooth flank load carrying capacities. Compared with variant 32CDV13, variants 30CrNiMo8 and 31CrMoV9 are classified with lower flank load carrying capacity in relation to the expected one. Even at relatively low nominal contact stresses, changes in the tooth flank condition occur in the running tests at low numbers of load cycles, which resulted in significant damages to the active tooth flank. In all the tests with tooth flank damage, erosion of the compound (white) layer was observed first, followed by damage to the tooth flank surface in the similar form of pitting. Compared with the results of the "basic" variant from [6], the test variants 30CrNiMo8 and 31CrMoV9 investigated here suggest a comparable flank load carrying capacity. In contrast, no significant change or damage to the tooth flank surface was detected once the limiting number of load cycles of 30 or 50 million load cycles had been reached in the test runs for variant 32CDV13, even in the range of high nominal contact stress (σ_{H0} = 2050 N/mm^2), which is clearly higher as the pitting durabiltiy levels for nitrided gears acc. ISO 6336-5 [2] and also clearly above the pitting durability of case hardened gears. Based on the available test results, a significantly higher flank load capacity can be estimated for variant 32CDV13. Due to the scope of the test on the flank load carrying capacity, an explicit classification of the results in the strength fields of ISO 6336-5 [2] was deliberately not done.

than the strength numbers for the highest material quality grade ME specified in ISO 6336-5 [2] for nitrided nitriding steels and can be classified in the middle resp. upper range of case hardened gears of comparable sizes. Nevertheless, the results also basically confirm the increased overload sensitivity known from literature [4] of nitrided gears even at increased nitriding depth. Based on the tests carried out on the tooth root load carrying capacity, no significant influence of the compound layer (e.g. thickness) could be derived. In summary, based on the studies conducted here, an increase in NHD leads to an increase in bending strength.

The running tests for the tooth flank carrying capacity indicate significantly different tooth flank carrying capacities of the investigated variants. If the compound layer is damaged or if it is not sufficiently thick, as in case of the variants 31CrMoV9 and 30CrNiMo8, the compound layer is eroded after only a few load cycles and the tooth flank will be damaged even at relatively low nominal contact stresses. In contrast, with a sufficiently thick compound layer without pre-damage (e.g. micropitting), as in case of the variant 32CDV13, flank load carrying capacities, that exceed the material specifications for nitrided nitriding steels according to ISO 6336-5 [2] can be expected. The variant 32CDV13 can be classified in the range of resp. above common material strength numbers for case hardened gears. Summarizing, it can be concluded that as long as the compound layer stays intact, a high flank load carrying capacity can be estimated. If the compound layer is damaged or starts to delaminate, a significantly reduced flank load carrying capacity can be observed.

To summarize: It can be stated that, as also shown by the test results from [4], an intact compound layer positively affects the tooth flank load carrying capacity. In the event of damage to the compound layer, however, a strong decrease in the flank carrying capacity can be expected.

5 Summary and conclusions

By nitriding, the load carrying capacity of gears, in particular the tooth flank and tooth root load carrying capacity, can be significantly increased. A good tempering resistance of the material is important for deep nitriding, as tempering effects can occur even below the tempering temperature of the pretempering due to the long treatment times. Good nitriding characteristics are also important in order to achieve treatment durations within the bounds of economic efficiency [9].

The experimental tooth root bending strength numbers determined for the investigated deep nitrided variants 31CrMoV9, 30CrNiMo8 and 32CDV13 were even higher

6 Outlook

Based on the promising results of the test variant 32CDV13, further experimental investigations are currently being carried out for statistically validated statements regarding the expected tooth root, and especially tooth flank carrying capacity, as part of the follow-up project FVA 615 III [19]. In addition, a further study on the influence of the compound layer during deep nitriding is currently in progress. For this purpose, investigations are being carried out on the load carrying capacity of deep nitrided gears in which the compound layer is ground off before use (which is standard practice in many companies today for conventional nitriding), and on gears with thick, compact compound lay-

ers, as in the case of the 32CDV13. The base material also has a significant influence on deep nitriding, since a high tempering resistance is essential for both the hardness in the core and in the nitrided layer during the long nitriding times. Therefore, investigations of alternative high-temperature materials with regard to their suitability for deep nitriding are currently ongoing.

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