Influences of the Residual Stress Condition on the Load-Carrying Capacity of Case-Hardened Gears

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Introduction

Highly loaded gears are usually case-hardened to fulfill the high demands on the load-carrying capacity. Several factors, such as material, heat treatment, or macro and micro geometry, can influence the load-carrying capacity. Furthermore, the residual stress condition also significantly influences load-carrying capacity. The residual stress state results from heat treatment and can be further modified by manufacturing processes post heat treatment, e.g. — grinding or shot peening.

A variety of investigations was performed in several research projects concerning the influence of residual stresses on the load-carrying capacity limits of gears. The investigations were focused on the tooth root bending strength as well as the flank load-carrying capacity. The gears were analyzed in un-peened, mechanical-cleaned, and shot peened condition. The investigations included different materials, e.g. — 16MnCr5 or 18CrNiMo7-6 — and different gear sizes.

Compressive residual stresses generated by shot peening, for example, result in an increased tooth root bending strength. The tooth root bending strength of shot peened gears can be increased by more than 50% compared to gears in the un-peened condition. Per mechanical laws, the increase of the load-carrying capacity is limited. In the case of highly loaded shot peened gears, other failure mechanisms may arise, such as subsurface-initiated cracks. Shot peening can also significantly increase the flank load-carrying capacity. Due to a shot peening process, the surface of the gears is influenced. As a consequence, other failure mechanisms can occur, such as micropitting. Furthermore, shot peening and the resulting compressive residual stresses can also be used to repair grinding burn or to avoid facing edge tooth flank fractures.

All in all, the investigations show that shot peening can significantly increase the load-carrying capacity of case-hardened gears. Furthermore, correlations between the residual stress state and the load-carrying capacity limits were determined. This paper will provide an overview of the main results of different investigations and discuss influences of the residual stress condition on different failure modes of case-hardened gears.

Case-hardening is a typical heat treatment process used to achieve an adequate load-carrying capacity of highly loaded components, such as gears. The challenge is always either to minimize the size of the component to transfer the same torque or force, or to be able to transfer a higher torque or force using the same size of the component. Several factors influence the load-carrying capacity of gears, such as material, heat treatment, or macro and micro geometry. Furthermore, the residual stress condition has a significant influence on load-carrying capacity; the residual stress state is changed during the manufacturing process by the heat treatment and a possible downstream shot peening.

Within the scope of this paper will be shown the influence of the residual stress state — especially influenced by a peening process — on the load-carrying capacity of gears. The main focus is set on the tooth root bending strength. Besides this, influences on the tooth flank characteristics will also be discussed. This paper will summarize the main results of different, previously published investigations. Therefore, the different projects are compared by showing the main results.

Characterization of Residual Stresses

Residual stresses are stresses which occur in a component that is not loaded by any force or torque. There are tensile and compressive residual stresses. Both kinds of residual stresses are balanced within a component. Compressive residual stresses in the surface layer typically have a positive influence on the load-carrying capacity, whereas tensile residual stresses in the surface layer can significantly *reduce* load-carrying capacity. The residual stress state is influenced by the manufacturing process, which includes soft-machining, heat treatment, and finishing. The "case-hardening" heat treatment process usually leads to compressive residual stresses in the surface layer and tensile residual stresses in the core. The residual stresses take only small compressive stress values in a range of about −200 up to −400 N/mm^2. During quenching the component does not cool down uniformly, so a volume difference occurs whereby residual stresses arise; furthermore, austenite transforms into martensite. Both microstructures have different yet specific volumes that result in additional residual stresses. All in all, the residual stress state results from a combination of quenching and volume change.

Usually the gears are subjected to a shot blasting or peening process after case-hardening. There is therefore a distinction between mechanical cleaning and shot peening. In both cases the generation of the residual stresses is based on the model representation of Wohlfahrt (Ref. 26). For case-hardened steels (e.g., 16MnCr5 or 18CrNiMo7-6), the residual stresses are generated by the elastic-plastic deformation of the surface. Due to the

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local stresses that exceed the yield point of the material, compressive residual stresses arise. Furthermore, as mentioned above, the retained austenite transforms into martensite during the shot peening process. Due to different specific volumes of the microstructures, compressive residual stresses arise (Ref. 22).

During the "grinding" finishing process, the residual stress state also changes in that the surface layer is mechanically and thermally influenced (Ref. 21). Due to the mechanical influence of the grinding wheel, compressive or tensile residual stresses may be generated. Excessive heat exposure during the grinding process results in tensile residual stresses. The residual stress condition post grinding is a result of a superimposition of both influences. The process parameters have a significant influence on the residual stress state. In the surface layer, tensile as well as compressive residual stresses may arise.

Mechanical Cleaning

The aim of the mechanical cleaning process is to remove the scale layer and clean the component after heat treatment. The process is mostly done by an impeller; a schematic presentation is shown (Fig. 1). The blasting material is mostly cut wire or glass beads. The process is not defined; only the process time and the speed of the impeller are controlled and monitored (e.g., 5 minutes-per-side). By this process, compressive residual stresses are induced that have a positive effect on the load-carrying capacity. Furthermore, according to ISO 6336-5 (Ref. 4), the bending stress numbers for case-hardened gears of material quality MQ are purposefully achievable with mechanical cleaning.

Shot Peening

Shot peening differs from mechanical cleaning. As opposed to blast cleaning, several parameters — such as blasting material, hardness of the blasting material, size of the material, degree of coverage, and intensity — are defined and monitored. According to ISO 6336 (Ref. 4), "The recommended minimum control should be based on SAE AMS 2430 (Ref. 16), SAE AMS 2432 (Ref. 17) or SAE J 2241 (Ref. 18)." The blast material in this case is steel balls, with the aim of a specific increase of the compressive residual stresses. The steel balls have to be round and the hardness of them has to be at least identical to the hardness of the component. Therefore, the steel balls are accelerated by jet nozzles. The size and hardness of the steel balls can be varied as well as the ejection speed (Fig. 2) and the duration of the process. Before the component is shot peened, a measurement of the intensity is done; on the basis of this measurement the peening time is determined. With these parameters the depth of the maximum and the maximum value of the residual stresses can be varied within some limits. Furthermore, the steel balls underlie a continuous processing in order to maintain a constant result of the shot peening process. Due to the comprehensive monitoring, the process can achieve reproducible results. To achieve the expected results of the shot peening process, the component has to be cleaned in advance.

In Figure 3 typical residual stress values

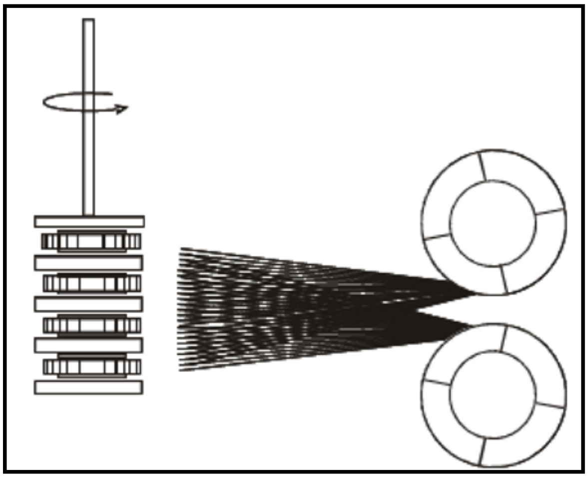


Figure 1 Schematic presentation of the mechanical cleaning by an impeller (Ref. 10).

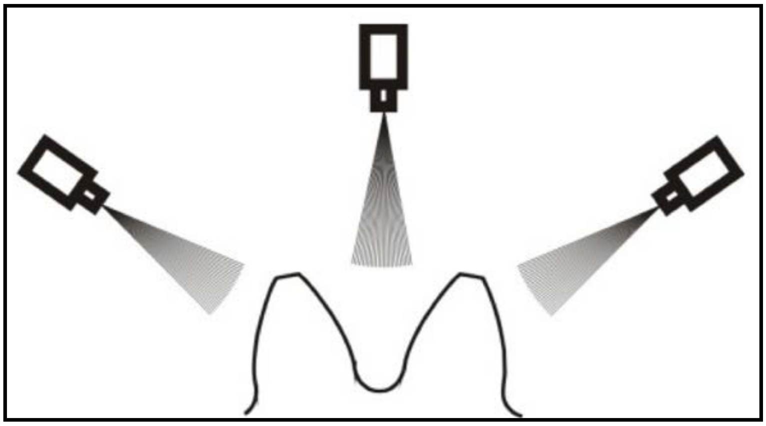


Figure 2 Schematic presentation of the shot peening by jet nozzle (Ref. 10).

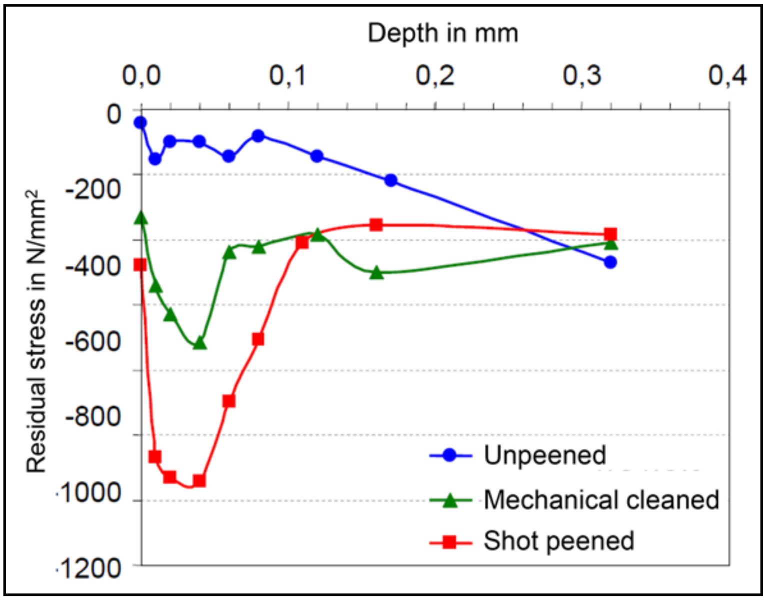


Figure 3 Comparison of the residual stresses in the un-peened, mechanical-cleaned, and shot peened condition (measurement results, exemplary presentation) (Ref. 22).

in the surface layer are plotted for gears in the un-peened, mechanical-cleaned, and shot peened condition. The influence of increased residual stresses due to mechanical cleaning or shot peening is limited to only a depth of about 0.1-0.15 mm. The highest compressive residual stresses are achievable with shot peening.

Furthermore, it is also possible to combine two shot peening processes with different parameters (Ref. 12). So, high compressive residual stress values on the surface, as well as high compressive residual stress values in a greater material depth, can be realized. In Figure 4 the residual stress states of different shot peening processes are compared to the un-peened condition. Here, a shot peening process with big steel balls (diameter of 0.8 mm) is combined with a shot peening process with small steel balls (diameter 0.1 mm), which is called WHSP. By this combination, high compressive residual stresses on the surface and high compressive residual stresses in greater material depths are achievable.

Another aspect of the shot peening process is that the roughness of the component/gear is influenced. Especially in the case of a grinded surface, the shot peening process often leads to a higher surface roughness compared to the grinded condition (Refs. 10 and 6). In Table 1 the surface roughness of a grinded tooth surface is compared to a grinded surface with an additional shot peening (after grinding). Due to the shot peening process, the measured surface roughness of the tooth flank increases from Ra ≈ 0.30 µm/Rz ≈ 1.97 µm after grinding to Ra ≈ 0.87 µm/Rz ≈ 4.76 µm after shot peening.

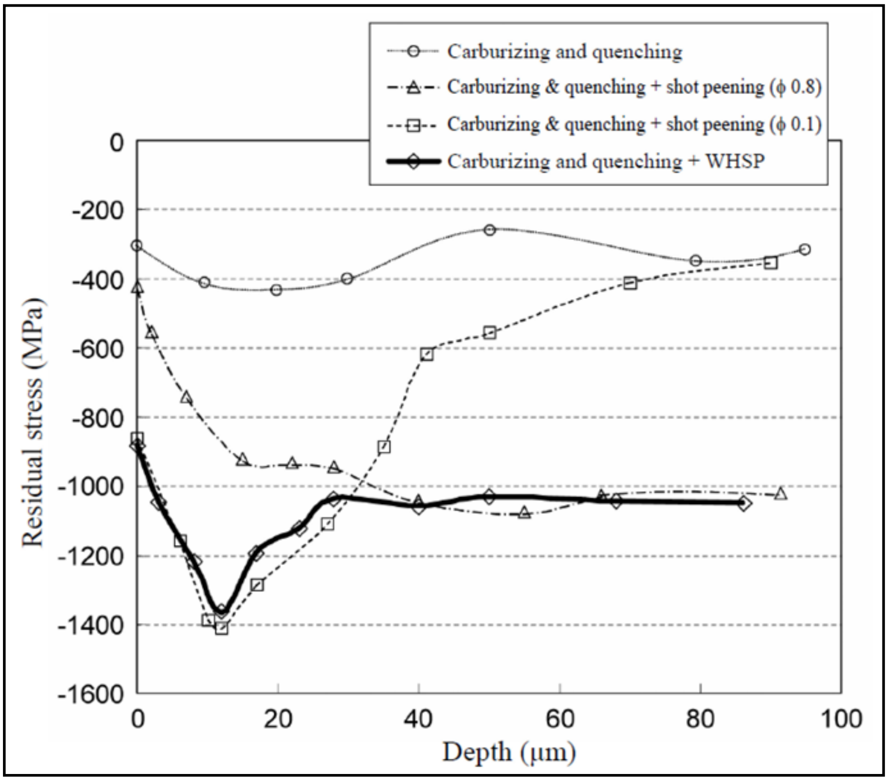
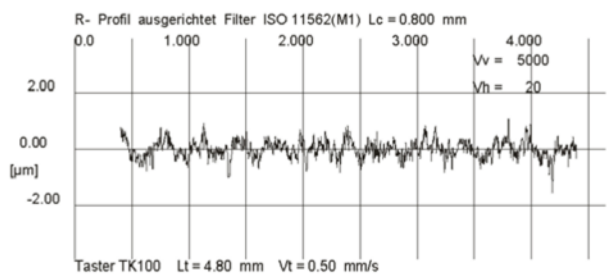
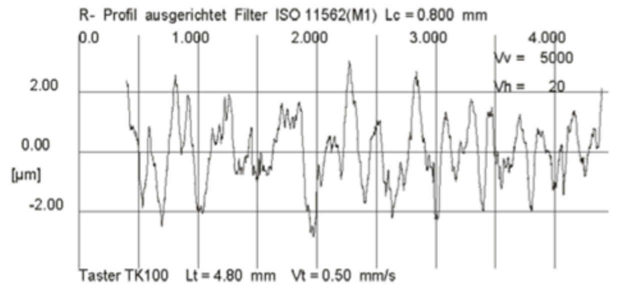


Figure 4 Comparison of the residual stress states generated with different processes (Ref. 12).

Table 1 Comparison of the surface roughness of a grinded gear surface and a grinded gear surface with an additional shot peening (after grinding) according to [10

Grinded	Grinded and shot peened (after grinding)
	

Investigations of the Gear Strength — Test Rigs and Test Conditions

Tooth root bending fatigue strength. The bending fatigue tests were carried out by means of an electro-magnetic, pulsating test rig (Fig. 5). 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 cross-beam by two rod springs. The test gears were symmetrically clamped and tested over a certain number of teeth (generally 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 offset by means of a precision adjustment, thus 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 normally

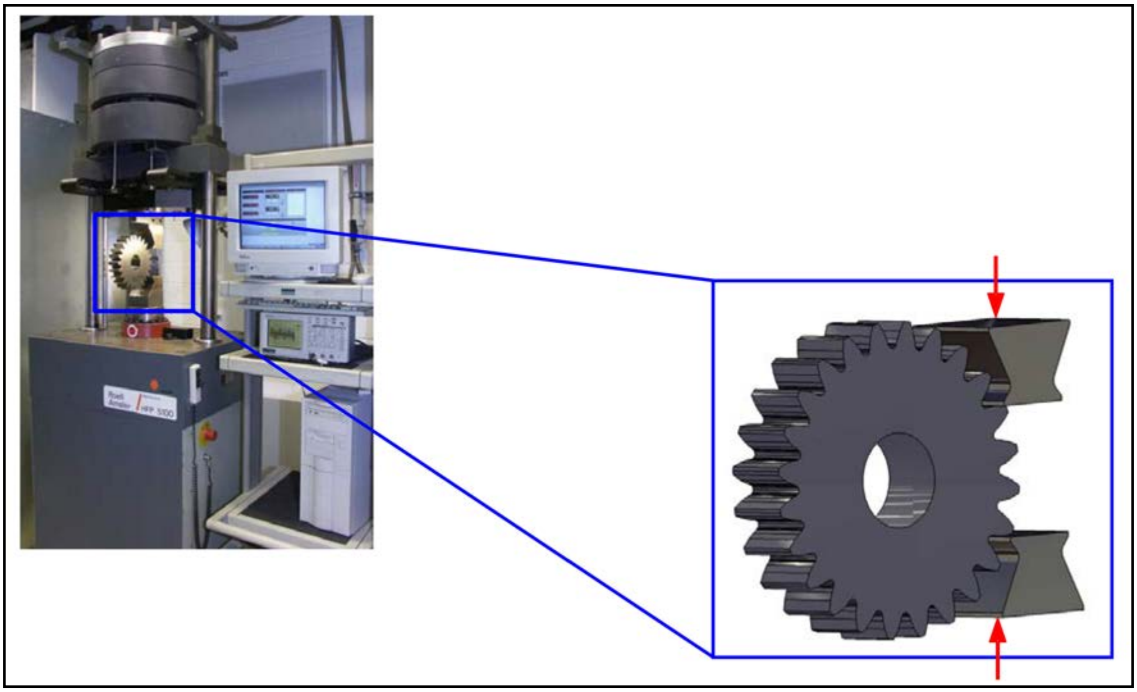


Figure 5 Pulsator test rig.

stopped after $6 \cdot 10^6$ load cycles. In case of the investigation of the high cycle fatigue, the load cycles were increased.

Tooth flank (contact) fatigue strength. The test runs for the determination of surface durability (pitting) were performed on FZG back-to-back gear test rigs, with a center distance of $a = 91.5$ mm. Figure 6 shows a picture of the test rig with a center distance of 91.5 mm. The test rig is driven by a three-phase, asynchronous engine with a constant speed of 3,000 rpm. Test pinion and test gear are mounted on two parallel shafts that 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 and 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 gearboxes in this closed power loop. For the tests described herein, the pinion was mounted on the torsion shaft and 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 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, 100 and 10^6 load cycles.

Influence on Tooth Root Bending

The investigations concerning the tooth root bending strength (Refs. 1, 19, 20, 22 and 25 were performed on the described pulsator test rig.

Increase of the load-carrying capacity. Due to the increase of compressive residual stresses on and near the surface of the gears by mechanical cleaning or shot peening, the tooth root bending strength of case-hardened gears can be increased. Investigations done by Weigand (Ref. 25) or Stenico (Ref. 22) dealt with the influence of blast cleaning and shot peening using case-hardened gears made out of 16MnCr5 and 18CrNiMo7-6. Different gear sizes were used, including module 1.75-8 mm. Weigand (Ref. 25) identified an increase of the tooth root bending strength of 30% (concerning material 16MnCr5, module 5 mm) and 15% (concerning material 18CrNiMo7-6, module 5 mm) between case-hardened gears in the un-peened condition, and in the blast-cleaned condition. By using two different shot peening processes the increase in the tooth root bending strength was of 35–45% (material 16MnCr5) and 30–50% (material 18CrNiMo7-6), compared to the un-peened condition.

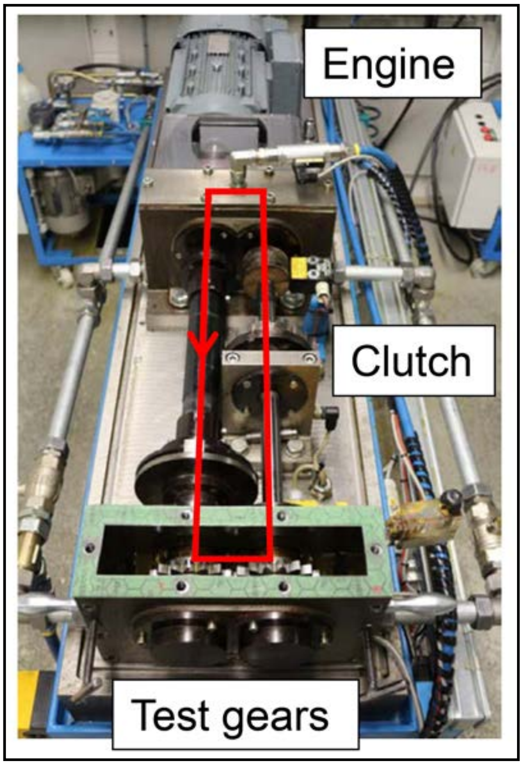


Figure 6 FZG back-to-back test rig.

Inoue et al. (Ref. 2) dealt with the effect of shot peening on the bending strength of carburized gears. In this research work, gears (module 5 mm) made of JIS SCM 415 and JIS SCM 420H were shot peened with different process parameters and different resulting residual stress states. The results show that an increase of tooth root bending strength of up to 30%, compared to the un-peened condition, is possible.

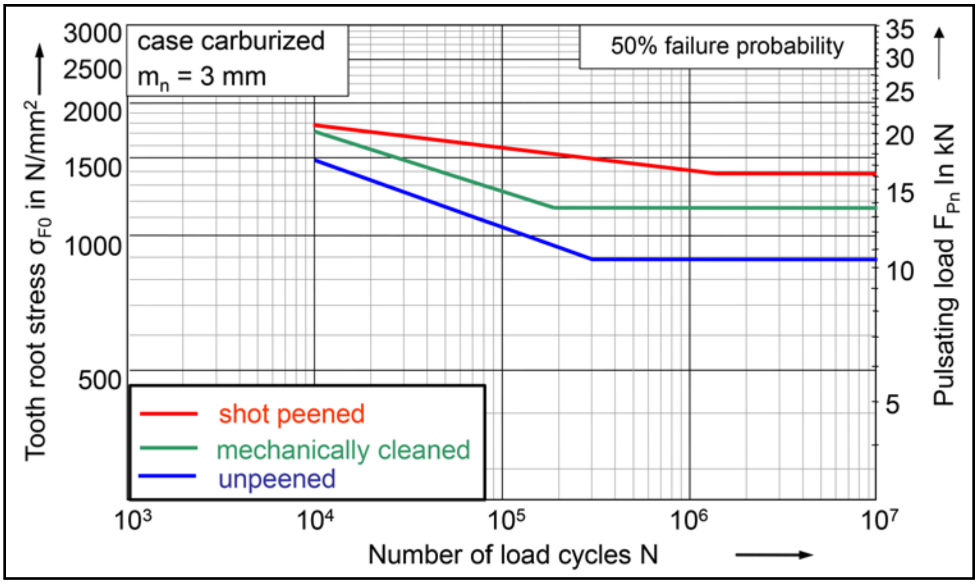


Figure 7 Exemplary presentation of the influence of mechanically cleaning and shot peening on the tooth root strength of a carburized gear (material 16MnCr5, module 3 mm) (Ref. 22).

Stenico (Ref. 22) investigated the influence of different shot peening parameters on the tooth root bending strength of case-hardened gears with different materials and gear sizes. The investigations revealed an increase of the tooth root bending strength of about 27%–43% for material 16MnCr5 (gear sizes 1.75; 3 and 5 mm) between the un-peened condition and after blast cleaning; the increase can be further enhanced by shot peening. With shot peening, the tooth root bending strength was about 42%–66% higher than in the un-peened condition. The material 18CrNiMo7-6 showed increases of about 38%–50% between the un-peened and shot peened condition for the gear size module 5 mm. In Figure 7 the determined S-N curves for the tooth root bending strength material 16MnCr5 (module 3 mm) are plotted in the un-peened, blast-cleaned and shot peened condition (failure probability 50%). The results prove that by blast cleaning or shot peening, the tooth root bending strength can be increased significantly. A consideration of the low cycle fatigue indicates that the slope of the low cycle fatigue curve gradient is different for the three variants. The un-peened variant has the highest value and the shot peened variant the lowest one. This means that blast cleaning, as well as shot peening, influences especially the endurance limit — but not the static tooth root bending strength. The consequence is that blast-cleaned — but especially shot peened — gears show higher overload sensitivities than gears in the un-peened condition. Furthermore, for gears, especially in the shot peened condition, failures due to subsurface cracks were detected.

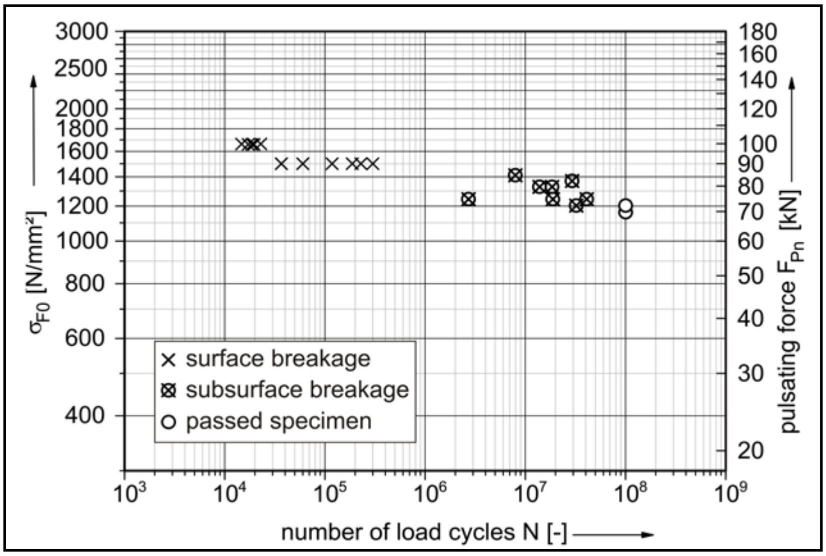


Figure 8 Tooth root bending test results of a shot peened variant at a cycle limit of 100 · 106 (Ref. 1).

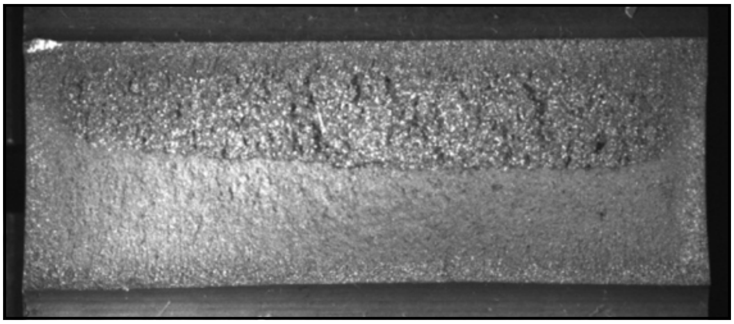


Figure 9 Typical tooth root fracture surface, crack initiation on the surface (Ref. 20).

Figure 8 (Ref. 1) presents the results of the tooth bending strength of the material 16MnCr5 (gear size module 5 mm) in the shot peened condition. The test runs were terminated after 100 · 10^6 load cycles. The test runs that fail in the range lower than 10^6 load cycles are characterized by surface-initiated tooth root fracture damages. In the range of higher load cycles, all breakages originate from the subsurface. Furthermore, the results show that the nominal tooth root stresses σ_{F0} of the failures in the range of more than 10^6 load cycles are lower than for breakages from the surface.

Change in the fracture mode — un-peened vs. shot peened condition. Case-hardened gears in the un-peened, and most of the gears in the blast-cleaned condition, fail due to tooth root breakages with a crack initiation on the surface. Figure 9 displays a typical tooth root fracture surface; typical load cycles for such damage are in the range of 10^5 to 10^6 load cycles.

Tooth root breakages of gears in the shot peened condition that fail in the region of endurance limit show mostly a different fracture surface compared to gears in the un-peened condition. The fracture surface contains a small, round and bright spot. In the literature, this is often called "fish-eye" due to the characteristic appearance; Figure 10 represents such a typical fracture surface. The crack is initiated on an inclusion (oxide) sub-surface. Shot peened gears in the range of endurance life usually fail in the range of more than 10^6 load cycles.

In Figure 11 the load stresses for different gear sizes are plotted, as well as a typical hardness profile of case-hardened gears. Furthermore, typical residual stresses of un-peened and shot peened gears are shown. The schematic distribution of the load stresses presents that the highest load stresses occur on the surface of the tooth root. Furthermore, it is shown that the decrease of the load stresses depends on the gear size, whereas the compressive residual stresses do not. Considering case-hardened gears in the un-peened condition, crack initiation occurs on the surface where the highest load stresses occur. By shot peening, the surface is strengthened and a crack initiation on the surface is virtually prevented. The crack initiation takes place sub-surface — usually at an inclusion or other defect of the material. Bretl (Ref. 1) developed a model that considers the local strength of the material. Thus the material strength is compared with the local stress situation. The material strength depends mainly on the hardness; the local stress situation is characterized by load stresses and residual stresses. Compressive residual stresses have a positive effect on the tooth root bending fatigue strength, and are taken into account in an appropriate way. According to this model, a crack can be initiated when the local stress situation exceeds the local load capacity of the material. An inclusion or defect in the material causes a local increase of the stresses that can lead to an excess of

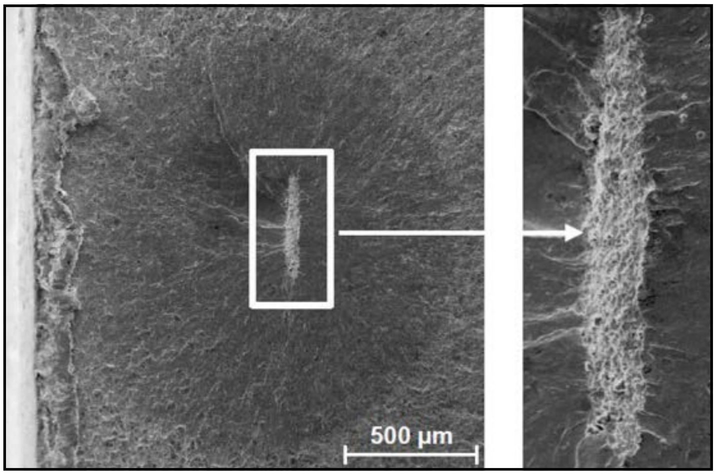


Figure 10 Typical tooth root fracture surface, crack initiation sub-surface on an inclusion (oxide) (Ref. 20).

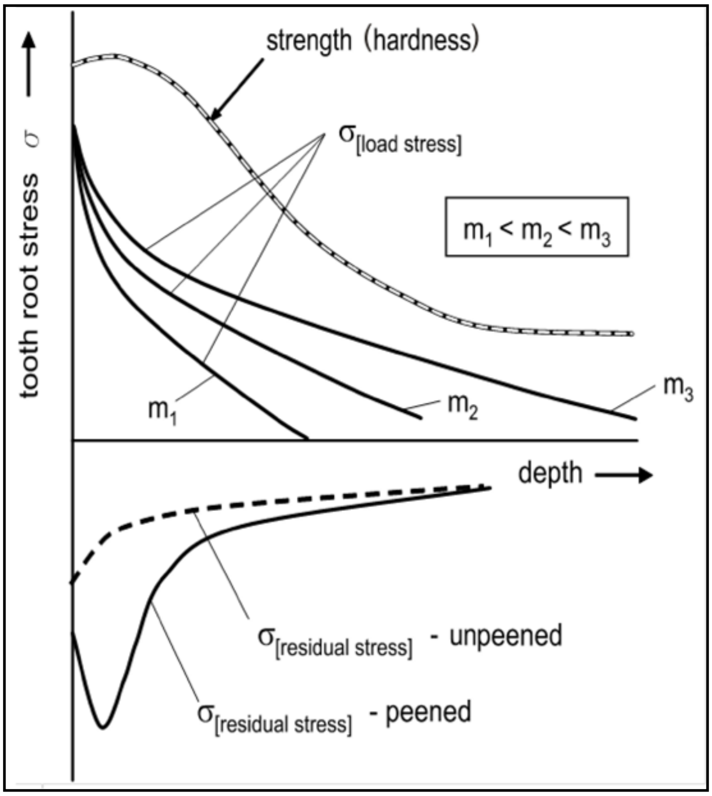


Figure 11 Schematic distributions of load stress, residual stress, and hardness in tooth root area of case-hardened gears depending on material depth (Refs. 1 and 19).

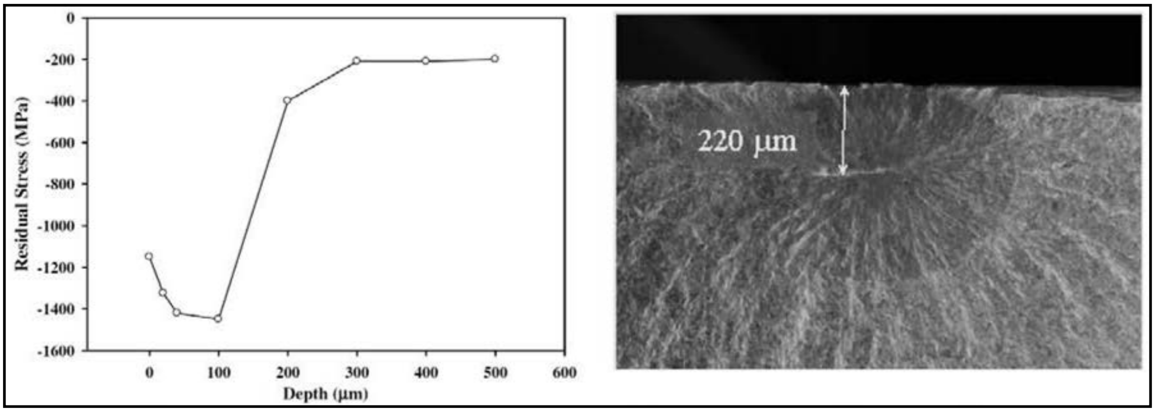


Figure 12 Residual stress distribution (left) and subsurface crack initiation (right) (Ref. 15).

the local strength, leading in turn to a subsurface crack. With the calculation model of Bretl it is possible to determine whether an inclusion can cause a crack that is growable.

Prasannavenkatesan (Ref. 15) determined that sub-surface crack initiation occurs in material depths in which the positive influence of the shot peening is lessened. Figure 12 shows that the residual stress state is plotted and the depth of the crack initiation is determined. The subsurface crack initiation took place in a material depth of about 220 µm. The maximum of the compressive residual stresses is located in a depth of about 100 µm. In a material depth of more than 200 µm, the compressive residual stresses of the shot peening are already subsided. This is also confirmed by the extensive investigations of Bretl (Ref. 1) and Schurer (Ref. 20). The results show that the crack initiation takes place in a material depth in which the high compressive residual stresses due to shot peening are subsided, but still remain within the case-hardened layer.

Stepwise S-N curve. All the results and theoretical considerations draw a conclusion that there is a kind of "double" S-N curve for the tooth root bending fatigue of shot peened, case-hardened gears; Figure 13 offers a schematic illustration of the stepwise S-N curve. In the literature it is also often called "two-fold" S-N curve. The "classical" S-N curve for tooth root bending strength is limited by crack initiation on the surface and is extensively validated for un-peened and blast-cleaned gears. Besides this, for shot peened gears, there is a second S-N curve that is determined by sub-surface crack initiation. This S-N curve determines the load-carrying capacity in the high cycle fatigue. Due to the sub-surface crack initiation, a further decrease of the tooth root bending strength has to be considered.

As shown in the research (Refs. 1 and 19), such two-step S-N curves also exist for un-peened and blast-cleaned gears. But because the surface is not strengthened by increased compressive residual stresses, the load-induced stresses exceed the fatigue strength at the surface before a critical stress condition below the surface can initiate sub-surface cracks. And so the crack initiation on the surface decisively determines the lifetime of un-peened and blast-cleaned gears.

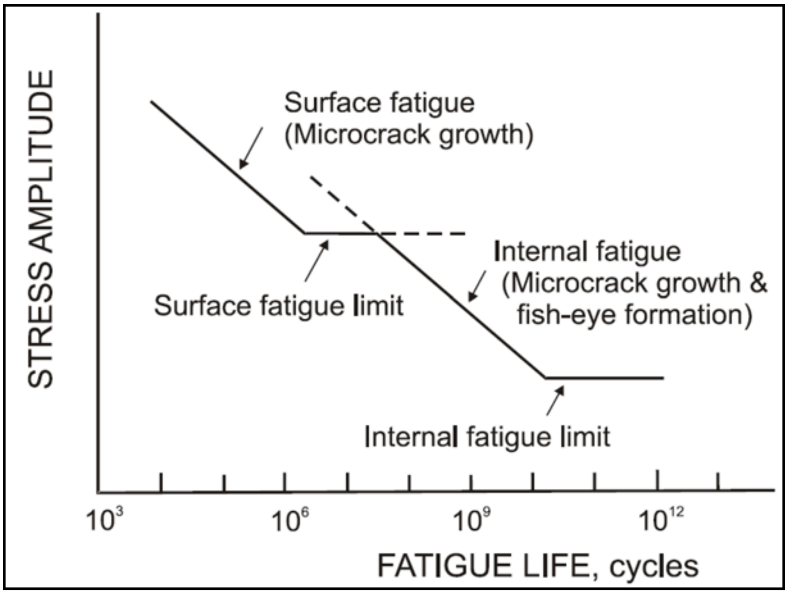


Figure 13 Schematic illustration of the two-step S-N curve (Ref. 14).

Influence on Tooth Flank Load Carrying Capacity

Investigations of the tooth flank load capacity were performed using the FZG back-to-back test rig. When the tooth root is mechanically cleaned or shot peened, the tooth flank is also influenced. For the tooth flank, there are several possibilities/manufacturing routes:

- Shot peening followed by grinding
- Grinding followed by shot peening
- Grinding, shot peening, and finally barrel-finishing

In the first case the grinding process removes the layer that is influenced by shot peening of the tooth flank. Grinding removes about 0.1–0.2 mm of the tooth flank; this is the material depth that is influenced by shot peening. In this case the residual stress state is decisively determined by the grinding process.

In the two other cases, the shot peening process can increase the tooth flank load capacity (pitting).

Increase of the Tooth Load-Carrying Capacity (Pitting)

In (Ref. 6) the influence of shot peening on the tooth flank capacity (pitting) was investigated. Therefore the gears were grinded (tooth flank) and then shot peened. The gears used in the investigation have a gear size of module 5 mm and were made out of 16MnCr5 and 18CrNiMo7-6 (old name: 17NiCrMo6). The results indicate that an increase of the tooth flank load-carrying capacity up to 10% is possible. Furthermore, especially concerning 16MnCr5, a correlation of the load-carrying numbers to the amount of retained austenite was detected. Regardless of the material, all shot peened gears have a higher surface roughness after shot peening, compared to the grinded state. Consequently, in the experimental investigations the shot peened gears showed a higher tendency toward micropitting. This type of damage can be reduced by using an adjusted oil with a higher micropitting load-carrying capacity.

Townsend (Ref. 24) investigated the influence of shot peening on the tooth flank load-carrying capacity of gears. Therefore some gears were additionally shot peened after grinding. The test runs were performed at a constant Hertzian stress. The gears that were shot peened showed a pitting lifetime that is about 46% higher than without shot peening. The increase of the load-carrying capacity is assumed to revert to the residual stress state. In a further investigation, the influence of the intensity (a middle one and a high one) of the shot peening process on the lifetime of case-hardened and shot peened gears was determined. After the shot peening the tooth flanks were honed to improve the roughness condition of the tooth flanks. The results show that the lifetime of the gears that were shot peened with the high intensity was 1.7 times higher than the lifetime of the variant with the middle intensity (failure probability 50%).

Due to the fact that a shot peening process often leads to increased surface roughness values, a further processing of the shot peened surface typically is necessary to use the potential of the flank load-carrying capacity. Therefore the influence of shot peening treatment and a finishing process was the focus in a research project (Refs. 10-11) to further increase the flank load-carrying capacity of gears. In experimental test runs the flank load-carrying capacity (pitting) of gears made of the material 16MnCr5 and a gear size of module 5 mm was determined. The finishing of the gears was varied, which included grinding, barrel-finishing and shot peening with an additional barrel-finishing. The results plotted in Figure 14 show that the highest pitting load-carrying numbers can be achieved by shot peening after grinding and an additional barrel-finishing. In this case the increase of the nominal contact stress for endurance was about 20% compared to the variant that was grinded. With the gain in the pitting load-carrying capacity, the risk of tooth flank fracture damage rises. Tooth flank fractures are characterized by a crack initiation subsurface in the area of the active tooth flank.

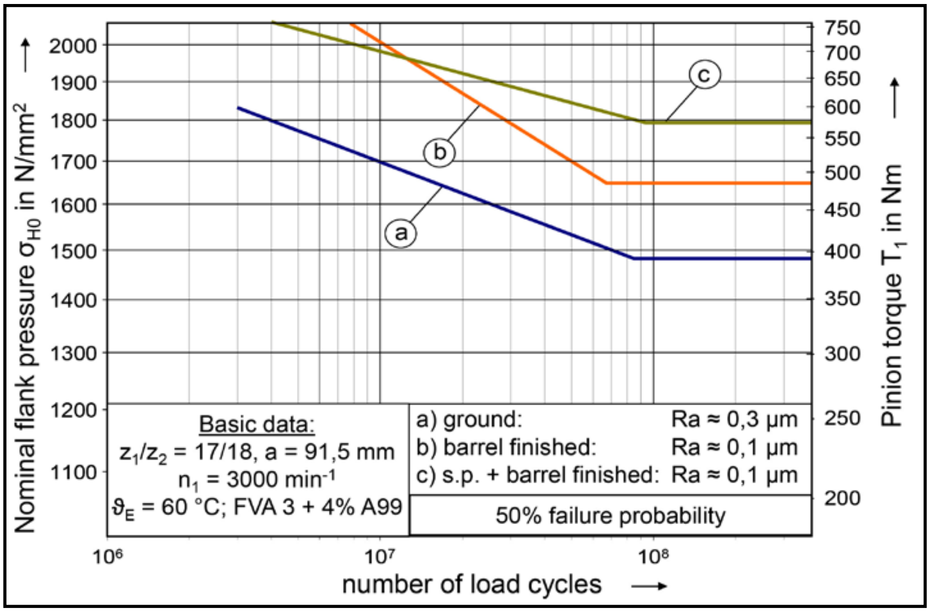


Figure 14 S-N curve of the pitting load-carrying capacity (s.p. means shot peening) (Refs. 10–11).

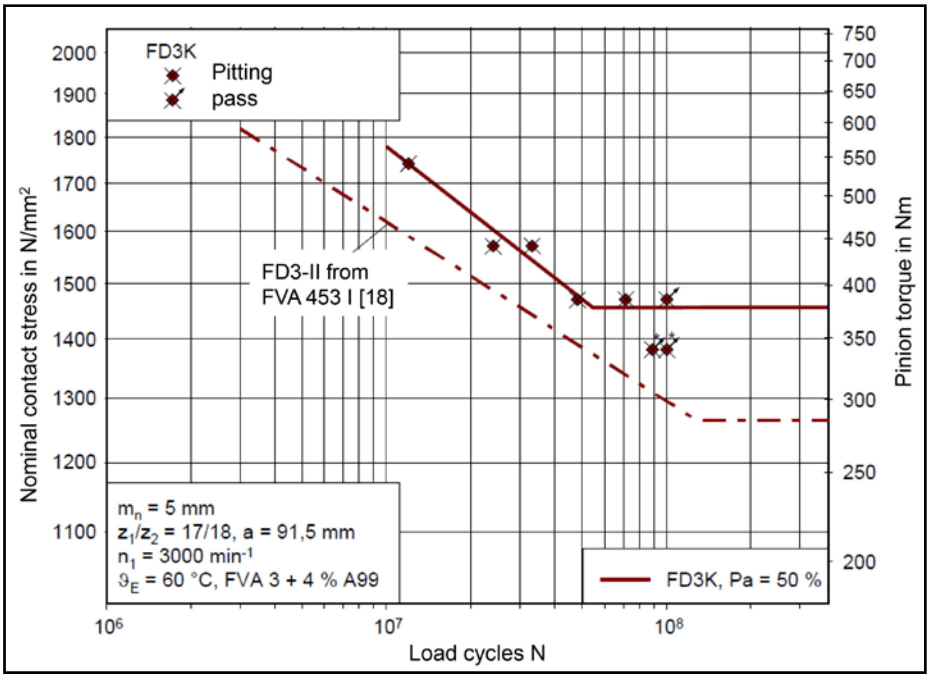


Figure 15 Exemplary presentation of the repair measure by shot peening and barrel-grinding of gears with grinding burn; FD3-II: variant with grinding burn; FD3K: variant with grinding burn that was shot peened and barrel-finished (Ref. 9).

Further Applications of Shot Peening

Repair measures for grinding burn. Grinding burn affects the material characteristics of the surface layer. As a consequence of grinding burn, the surface hardness decreases and even tensile residual stresses can arise. The tooth flank load capacity (pitting) is influenced in a negative way, which leads to a significant decrease of the load-carrying numbers. A downstream shot peening process of the gears with light-to-medium grinding burn can increase the load-carrying capacity of gears. According to (Ref. 6), load-carrying numbers comparable to gears without grinding burn are achievable; but the scatter of results is greater compared to gears without grinding burn. This results from the fact that the shot peening process cannot influence the whole damaged layer (Ref. 6). According to (Refs. 7–9; 21) a reliable repair is only possible concerning light-to-middle grinding burn (maximum FB according to ISO 14104 (Ref. 3)). Shot peening and barrel-finishing are necessary repair measures because shot peening not only increases the compressive residual stresses but also increases the surface roughness. Thus enhancement of the lifetime is possible, generally speaking, but the lifetime is limited due to local wear as well as a local modification of the tooth profile. In Figure 15 the influence of the repair measure shot peening and barrel-finishing for gears with grinding burn is shown. Variant FD3-II is damaged by grinding burn, variant FD3K is additionally shot peened and barrel-finished. The results prove that by shot peening and barrel-finishing, the tooth flank load capacity (pitting) of gears with grinding burn can be increased up to a level compared to gears without grinding burn. The underlying mechanism includes the following two aspects: due to the shot peening, the tensile compressive residual stresses are changed into compressive residual stresses. Furthermore, the barrel-finishing achieves a fine surface structure. In the case of a strong grinding burn, the tensile residual stresses reach deeper into the material, which cannot be completely changed into compressive residual stresses by shot peening.

To sum up, shot peening can be used to repair grinding burn if the tensile residual stresses in the surface layer can be changed into compressive residual stresses, and if a sufficient surface quality can be achieved. The grinding burn up to class FB according to ISO 14104 can be repaired.

Avoiding facing edge tooth fracture. Facing edge tooth fracture is an unexpected tooth flank fracture that is sometimes observed on helical gears (Fig. 16, left). The crack initiation takes place in the area of the acute facing edge. This kind of damage reduces the tooth flank load capacity. In a research project the influence of face end modifications to avoid face edge tooth fractures on helical gears was investigated (Fig. 16, right).

A shot peening of the face side increased the face edge load-carrying capacity. Instead of face edge tooth fractures, the helical gears failed due to tooth breakage or pitting (Refs. 5 and 13). The results also prove the positive effect of compressive residual stresses that strengthen the face side in this case. This strengthening of the face side leads to an increased tooth flank load-carrying capacity.

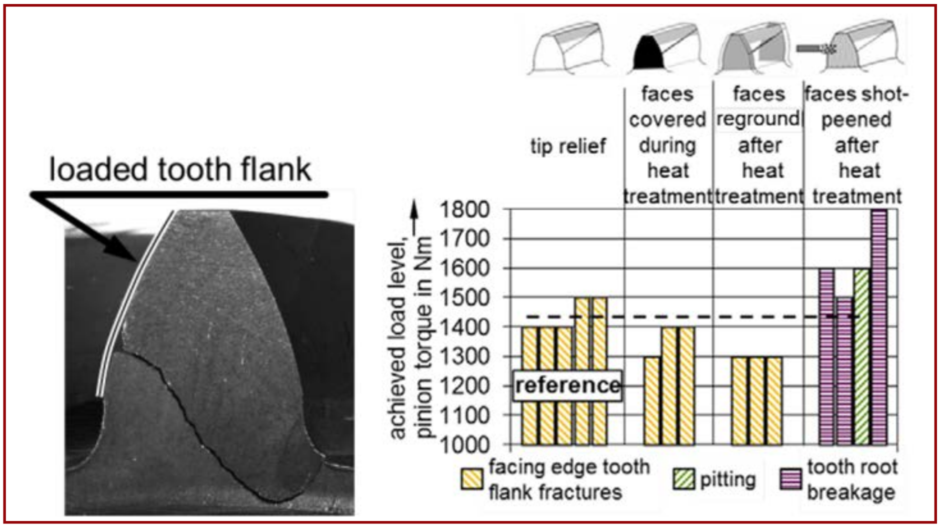


Figure 16 **Left: typical face edge tooth fracture, view on the face side (Refs. 5 and 13); Right: influence of face end modifications on load-carrying capacity (Refs. 5 and 13).**

Conclusion

There are tensile and compressive residual stresses that are balanced in a component that is not loaded by any torque or force. The residual stress state is influenced by many factors, such as manufacturing or heat treatment. Furthermore, the residual stress state can be further modified by blast-cleaning or shot peening. In dependence of the process parameters, high compressive residual stresses up to –1,200 N/mm^2 can be achieved.

There are numerous investigations concerning the influence of the residual stress condition on the load-carrying capacity of case-hardened gears. These investigations highlighted that compressive residual stresses have a positive influence on the load-carrying capacity, whereas tensile residual stresses decrease the load-carrying numbers. The tooth root bending strength can be increased by more than 50% by shot peening, compared to the un-peened condition. But in the case of shot peened gears, the failure mode may change from surface crack initiation to subsurface-initiated cracks, which can limit the tooth root bending strength and benefits from shot peening. A shot peening of the grinded tooth flank can also increase the flank load-carrying capacity (pitting). But as a consequence of the shot peening, surface roughness increases, too. Due to a higher surface roughness on the tooth flank, the risk of micropitting rises. For a further increase of the pitting load-carrying numbers, a barrel-finishing after shot peening is possible. Then, increases of up to 20% are achievable. Nevertheless, also for the tooth flank, the risk for subsurface-initiated damages (tooth flank fracture) may increase with increased, allowable transmitted torque based on the benefits from shot peening on the pitting load-carrying capacity. Another benefit of shot peening and the resulting compressive residual stresses is that it can be used to repair grinding burn to a certain degree, or to avoid facing edge tooth flank fractures.

All in all, by shot peening and the resulting high compressive residual stresses in the surface layer, the load-carrying capacity of case-hardened gears can be increased significantly. But other failure modes have to be considered, which may come to the foreground in highly loaded gears.

In order to benefit from the advantages of increased, compressive residual stresses in the surface layer, increased requirements on further gear characteristics may need to be considered. This includes, for example, gear materials with high purity to reduce the risk of subsurface-initiated failures, fine tooth flank surfaces and high-performance lubricants to reduce the risk of micropitting and wear, as well as an adequate macro and micro-geometry with adapted modifications of the gears.

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