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Fatigue test results of surface hardened components to evaluate a two layer approach for strength assessment

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Abstract

In the automotive industry, forged steels are commonly used for powertrain components such as gears, axles or crankshafts. In order to minimize wear and increase fatigue strength, these mechanical engineering parts are usually surface-hardened. The surface heat treatment leads to a significant change of the local material properties in the heat effected zone of the surface area.
This paper addresses an effective two-layer model for evaluating fatigue strength of surface hardened components based on local stresses. Hence, one layer represents the induction-hardened surface and the second characterizes the base material. The aim of this elaborated method is a more reliable computational estimation of fatigue life among other assessments based on technological benefit factors for components designed for the high cycle fatigue (HCF) regime by taking into account local material properties, defects and residual stresses.
In order to verify the presented method and to determine the local manufacturing process-dependent fatigue strength, specimens are extracted from highly stressed component areas considering forged grain structure. The sample notch shape represents typical notch types in mechanical engineering parts regarding form factor, stress gradient and highly stressed volume. The idea behind the fatigue tests is to study material samples exhibiting a comparably minor residual stress condition in both hardened and unhardened condition to separate the cause variables residual stresses, strength of base material and martensitic phase on fatigue strength. Compared to the unhardened base material, the fatigue tests at different stress ratios revealed higher fatigue strength within low and high cycle fatigue of the martensitic material.
Considering these input data in combination with the fatigue strength of each material section, the layer approach enables a more reliable local fatigue assessment among other fatigue evaluation methods based on technological benefit factors.

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Keywords: fatigue strength, surface-hardened components, residual stresses

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Present automotive products within continuous development process are subjected to the claim of consistent vehicle light weight design[1]. Hence the declaration of component safety has a high priority. In the automotive industry highly-stressed structural parts such as gears, axles or shafts are usually surface-hardened with the aim of minimizing wear and pitting[2] and increasing fatigue strength[3]. In comparison to weight-critical or package limited design changes surface-hardening achieves efficiently an ascending fatigue strength[4]. Thermochemical surface-hardening techniques[5, 6] causing further strength enhancement due to heat treatment are e.g. nitriding, case and induction hardening[7]. Within the heat affected zone processes of microstructure transformation and development of compressive residual stresses[8] occur. As depicted in Fig. 1 crack initiation beneath the surface layer according to different mean stress sensitivies of martensitic structure and base material at stress ratio $R = -1$ is possible. Mentioned effects regarding the different hardening processes are taken into account within fatigue design guidelines[9]. For ensuring an appropriate computational fatigue design this paper evinces a two layer material approach considering different material properties of the surface-hardened layer and the subjacent core material. A forged crankshaft with induction hardened main and conrod bearing areas is considered. Latter areas possess a martensitic structure as a result of the induction hardening process. Small-scale round specimens are extracted from crankshafts and uniaxial fatigue tests for both layers incorporating varied specimen hardness are pursued. As base material a AFP steel is used, which is common for forged and induction hardened components.

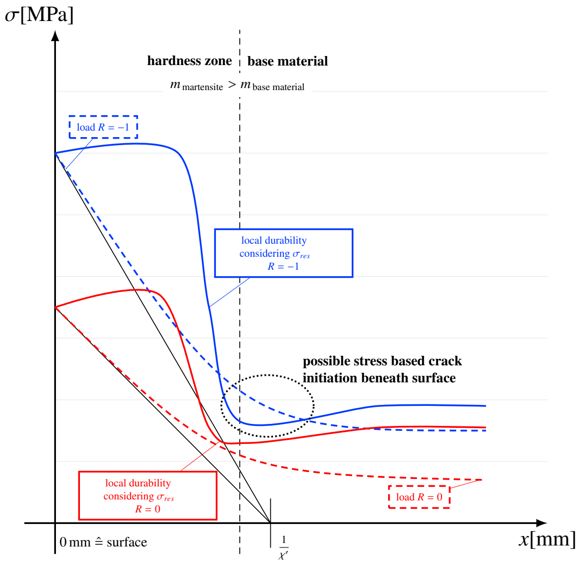


Fig. 1. Mechanical load vs. mechanical durability of surface hardened components

Nomenclature

σ_{res}	residual stresses [MPa]
α	angle of notch [°]
D,d	diameter [mm]
r_1	radius unnotched specimen [mm]
r_2	radius notched specimen [mm]
L	specimen length [mm]
R	stress ratio [−]
k	slope [−]
σ_a	nominal stress [MPa]
σ_m	mean stress [MPa]
N	load cycle [−]

2. Specimen preparation

During specimen preparation blanks are extracted from crankshaft considering forged grain structure, see Fig. 2. The partially detached cuboidal blocks represent base material of forged crankshaft steel. Half of the blanks are subsequently transformed into martensitic microstructure via oven hardening. The obtained crankshaft blanks represent on one hand the induction hardened surface layer and on the other hand the forged base material. Latterly the notched and unnotched specimen geometry is manufactured out of present cuboidal blanks. The final shape of the notched specimen is approximated to crankshaft fillet regarding form, stress gradient an highly-stressed volume, see Fig. 3. The idea behind the presented layer approach is to study specimens in untreated and hardened condition, which exhibit a comparably minor residual stress condition, in order to separate cause variables like residual stresses, strength of base material and martensitic phase on fatigue strength.

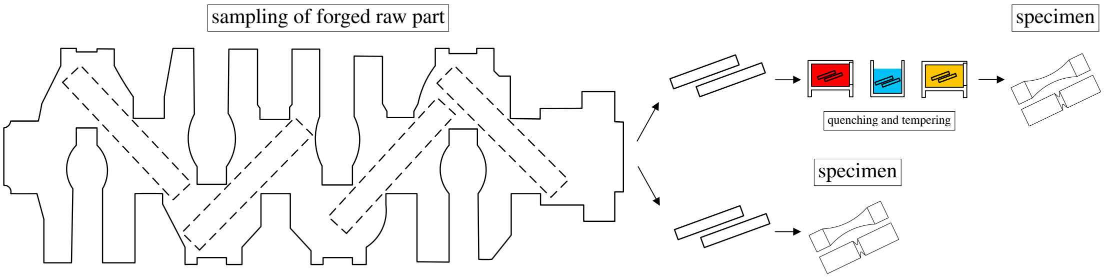


Fig. 2. Specimen preparation

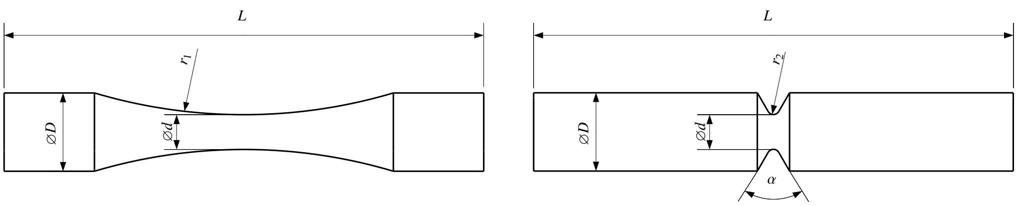


Fig. 3. Unnotched (left) and notched (right) specimen geometry for fatigue tests

Fig. 4 outlines via sectioning the hardened main and conrod bearing areas. The foundation for hardness profile in the depth direction from hardened surface to base material illustrates Fig. 5. The results are normalized to the maximum degree of hardness of the surface layer and hardness path length. Hardness measurements of the hardened specimens reveal an equal level in comparison to the crankshaft bearing area, see Fig. 6. Metallographic investigations attest the resulting martensitic microstructure of the fully hardened specimens. For the sake of completeness the hardening profile of the unhardened specimen is mentioned, see Fig. 7. Fig. 8 illustrates the to yield strength normalized axial residual stress depth profile of a crankshaft bearing. Final residual stress measurements of prepared specimens reveal a low residual stress state for unhardened specimens. The compressional residual stresses for hardened specimens are inferior in comparison to the maximum crankshaft condition.

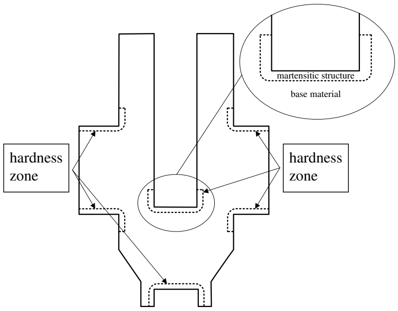


Fig. 4. Crankshaft section

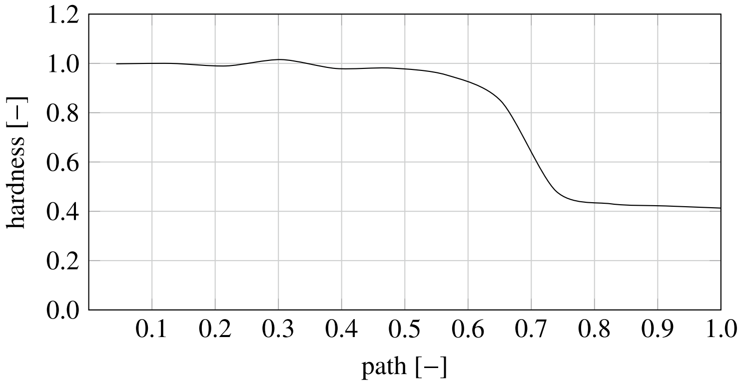


Fig. 5. Normalized hardness profile of crankshaft bearing in depth direction

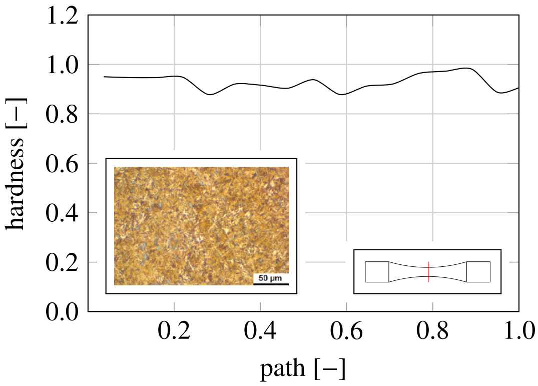


Fig. 6. Normalized hardness profile of hardened specimen

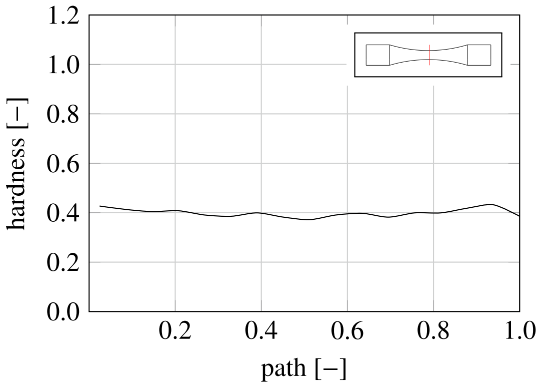


Fig. 7. Normalized hardness profile of unhardened specimen

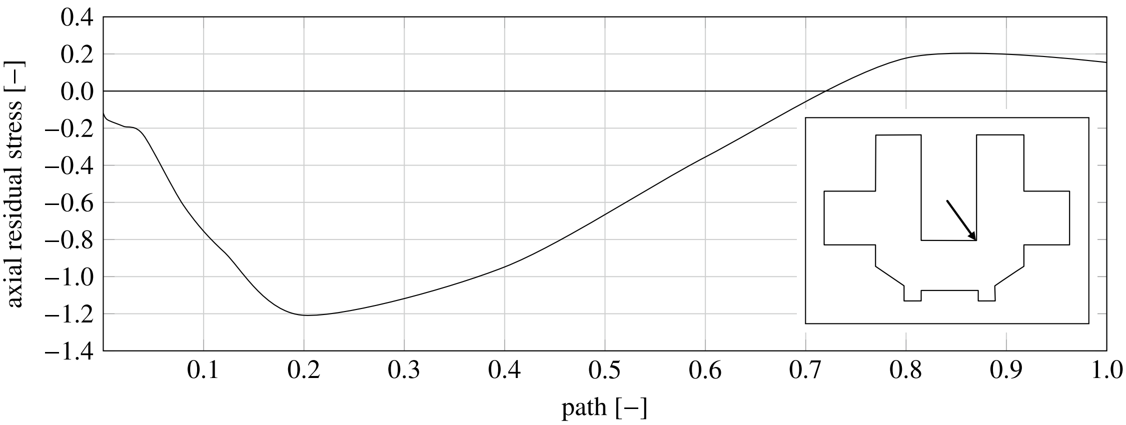


Fig. 8. Normalized residual stress depth profile of crankshaft bearing

3. Fatigue Tests

Table 1. Summary of fatigue test scheme

	tension-compression				bending	torsion		axial + torsion	
stress ratio	$R = 0$	$R = -\infty$	$R = -1$	$R = -1$	$R = -1$	$R = 0$	$R = -1$	$R = -1$	$R = -1$
phase shift								$\varphi = 0°$	$\varphi = 90°$
temperatur / specimen	20 °C	20°C	20°C	150°C	20°C	20°C	20°C	20°C	20°C
unnotchted, untreated, Rz1	✓	◯	✓	◊	◊	◊	◊	◯	◯
unnotched, hardened, Rz1	◊	◯	✓	◯	◊	◊	◊	◯	◯
unnotched, hardened, Rz16	◊		◊		◊				
notched, untreated, Rz1	✓	◯	✓		◊	◊	◊	◯	◯
notched, hardened, Rz1	◊	◯	◊	◯	◊	◊	◊	◯	◯

For the characterization of the aforementioned material conditions uniaxial and multiaxial fatigue tests are performed. Tab. 1 lists the completed (✓), current (◊) and future (◯) experiments. Cyclic tension-compression tests at stress ratio of $R = -1$ are executed for comparative purpose. Fig. 9 and 10 depicts the normalized results to the minimal run-out load level (nominal stress) of the notched unhardened specimen. The results reveal the fatigue strength of the hardened specimens is expactedly greater than the run-out load level of untreated base material. The comparison of run-out load levels leads to a normalized value of 1.86 for the unhardened specimen without notch geometry. The hardened counterpart reaches 3.67 for the run-out load level, see Tab. 2. Resulting cyclic tests at $R = 0$, see Fig. 11 lead to the Haigh-diagram for the unhardened base material according to Fig. 12. The fatigue tests demonstrate that the heat treated surface area possesses a generally increased fatigue strength compared to the untreated base material. The knowledge of fatigue strength of the two material layers enables the consideration of different material properties within computational fatigue design for surface-hardened components.

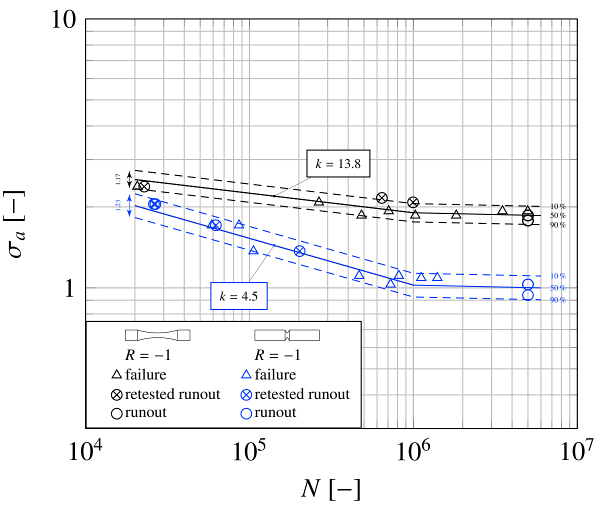


Fig. 9. Normalized fatigue test data of unhardened specimen

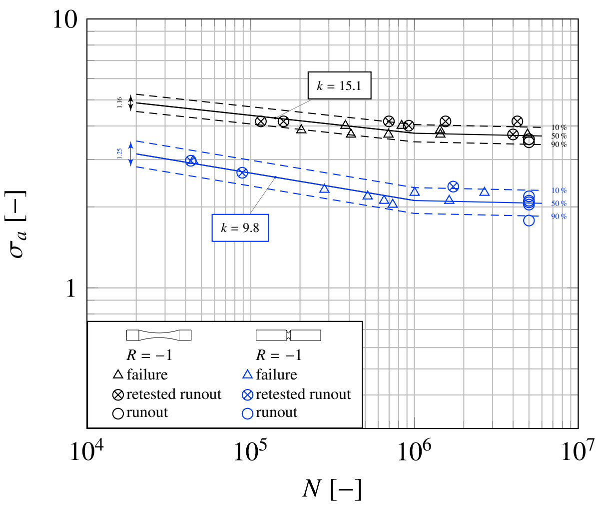
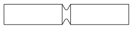


Fig. 10. Normalized fatigue test data of hardened specimen

Table 2. Normalized resulting run-out load levels of hardened specimens and base material

specimen	normalized unhardened run-out load level [−]	normalized hardened run-out load level [−]
	1.86	3.67
	1.00	2.06

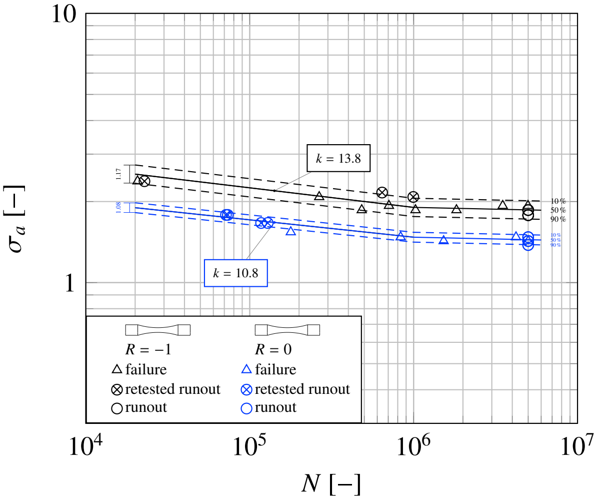


Fig. 11. Normalized fatigue test data of unhardened specimens

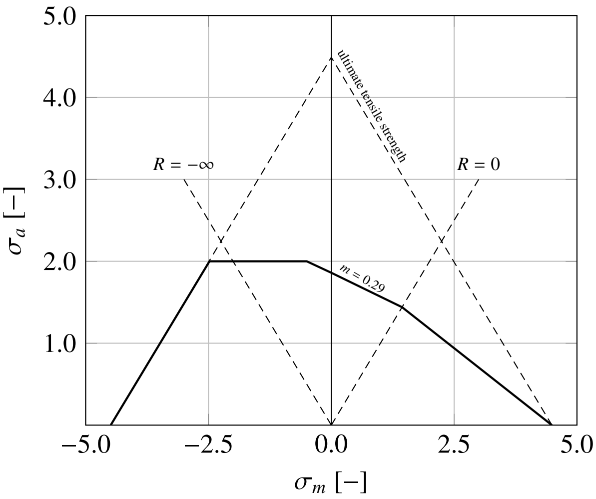


Fig. 12. Normalized haigh-diagram of unnotched, unhardened specimen

4. Computational Fatigue Design

The computational fatigue design is based on stress gradient approach according to [10, 11]. Input data are static and cyclic strength, which are investigated based on small-scale round specimens according to section 3. By usage of the specimen/component diameter and the local stress gradient of the highly-stressed component notch the local component Woehler-curve can be assessed, which acts as basis for the fatigue design. To include the hardenend surface layer the experimentally evaluated specimen Woehler-curve for the hardened material is included. The result is a number of local Woehler-curves of the component which will serve damage accumulation and component safety estimation, see Fig. 13. The advantages of the presented two-layer model can be summarized as follows:

- Separation of surface-hardened and subjacent core material, which improves the accuracy of the fatigue assessment
- Consideration and mapping of component residual stress state based on simulation
- Individual local stress-based fatigue design of both layers considering microstructural properties, load mean stress and residual stress condition as well as notch sensitivity
- Presented method acts as engineering-feasible fatigue design concept, which can be easily applied also for other material types and surface-hardening processes

Prospective work deals with the validation of the presented two-layer model with component fatigue data and the set-up of a feasible simulation technique to estimate the local residual stress condition of surface-hardened components, which acts as input data for the two-layer fatigue design approach.

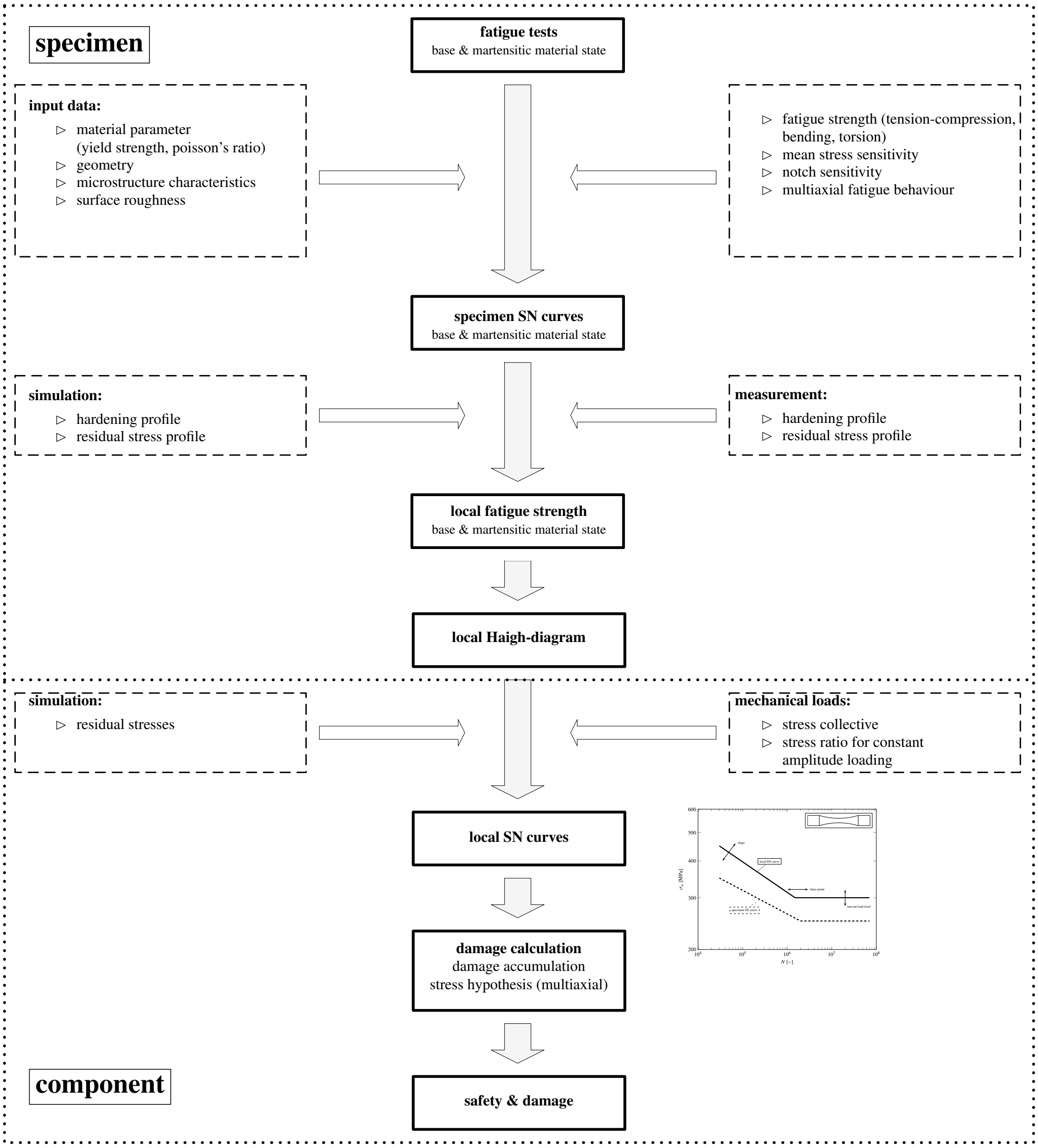


Fig. 13. scheme for computational fatigue design according to [10, 11]

5. Conclusion

This paper introduces an approach for the consideration of local different fatigue properties induced by surface hardening processes. To characterize the fatigue behaviour of the hardened surface layer reliable small-scale round specimens are extracted from automotive steel crankshafts and tempered to an equal hardening level as the bearing areas. Cyclic fatigue tests at a load stress ratio $R = -1$ revealed an increased fatigue strength of the martensitic material compared to the untreated base material. Based on the experimental results, the methodology of the two-layer approach is presented, which contributes to an improved fatigue design of surface-hardened components.

Further investigations will focus on cyclic fatigue tests at different stress ratios as well as additional loading types and elevated temperature effects. The aim is the characterization of mean stress sensitivity of the hardenend and untreated carboned steel. Cyclic testing under bending, torsion and combined loads will complete the scope of experiments and enable the application of the presented two-layer approach. A comprehensive validation of the concept acts as major task for the subsequent research work.

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