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SMART GREEN AND INTEGRATED TRANSPORT

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DETERMINATION OF DESIGN PARAMETERS

Detailed analysis methodology

ZF Luftfahrttechnik GmbH

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SUMMARY

Problem area

The aim of this report is to describe the methodology for the following test campaign in advance of the inital test plan (D2-3 report of this project, see bibliography) based on the contract between EASA and ZFL [2] and the EASA tender [1] according the “Horizon 2020 Work Programme Societal Challenge 4 - Smart, green and integrated transport”.

Description of work

In the frame of stream 2 of the project, this will be done by further analysis and tests as far as applicable. Therefore, the methodology of determining design limitations and crack prevention factors as well as the development of the reliability level is described in this report.

Results and Application

The methodology of determining design limitations and crack prevention factors, as well as the development of a reliability level, was described within this report.
This report can be seen as a baseline for the further definition of the test plan and gives a general explanation of the intention of the required tests, the targets to be achieved and the tools to be used.

CONTENTS

ABBREVIATIONS

ACRONYM	DESCRIPTION
CRB	Cylindrical roller bearing
DFG	Deutsche Forschungsgemeinschaft (engl.: German research community)
DoE	Design of experiments
EASA	European Union Aviation Safety Agency
EDM	Electronical discharge machining
EHL	Elasto-hydrodynamic lubrication
FE	Finite element
FVA	Forschungsvereinigung Antriebstechnik (engl.: research association drive technology)
ISO	International standard organization
RCF	Rolling contact fatigue
TBD	To be defined
SFB	Sonderforschungsbereich (engl.: special research area)
SPP	Schwerpunktprogramme (engl.: priority programs)
SRB	Spherical roller bearing
ZF	Zahnradfabrik Friedrichshafen
ZFL	ZF Luftfahrttechnik GmbH
1D	1-dimensional
2D	2-dimensional

1. Introduction

The aim of the report D2-2 (detailed analysis methodology) is to describe the methodology associated to the task 3 to 5 based on the contract between EASA and ZFL [2] according the EASA tender [1] of the ”horizon 2020 work programme societal challenge 4 - Smart, green and integrated transport”.
The required report is a part of stream 2 of the project and can be seen as a useful prework to prepare the initial test plan (D2-3 report of this project, see bibliography) and work out of adequate design limitations and crack prevention factors for bearings with integrated raceways.

This report will provide detailed information about the simulations and tests used during stream 2 of the project by also focusing on the underlying methodology and associated tools and rigs that will be used for said simulations and tests, especially for crack propagation. A detailed description of the test rigs will be provided, to show their capability and flexibility to fulfill the needs of this project.

Moreover, the approach of determining the values, sizes and levels of the parameters will be described and well-founded. Not only the variable parameters, but also those that are fixed during the tests will be described and explained. Based on the chosen parameters, the necessary number of test points/simulations will be described and the detailed method during testing and simulation will be clarified.

As a final step of this report, it will also be shown how the selected simulations and tests are used to conclude appropriate design limits for the selected key design parameters.

Chapter 2 provides the context of this report within the goal of the project

Chapter 3 describes the fundamental background for methodology approach

2. Placement in the context of the project

In [3], the most significant design parameters (key design parameter) for bearings of rotor and rotor drive system components that will influence the reliability and tolerance to flaws of these components when subject to rolling contact fatigue were ranked and identified. A selection of the evaluated parameters shall be used in a further step to define a methodology for the testing, simulation and limitation of these parameters. The approach shall be presented within this report. The overall target is to reduce the number of catastrophic failures of rotor and rotor drive systems of a helicopter.

Based on the investigations in [3], a pre-selection of the key design parameters was already carried out according to their criticality. An overview of the priorized parameters is given in Table 1. The parameters are divided into three different groups. On the one hand parameters that are suitable for conventional bearings (non integrated raceways) and bearings with integrated raceways and on the other hand parameters that have particular properties for bearings with integrated raceways or planetary gears with integrated raceways. Finally, they all share common ground in that they contribute to the reliability and flaw tolerance of the bearings of rotor and rotor drive systems.

Parameter	Rationale
Parameters suitable for all bearings	
Roller raceway full contact & truncation	Stress peaks leading to higher risk of RCF
Contact Stress	High stress amplitudes leading to high risk of RCF. A main parameter contributing to the contact stress is the roller profile
Misalignment	Misalignment leads to high local stress peaks and risk of RCF
Slippage and P.V.	Slippage leads to increased wear. In case of crack initiation it could lead to a load situation facilitate crack propagation
Lambda ratio lubrication	Ratio is directly linked to risk of spalling and therefore reliability of the raceway
Oil cleanliness / pollution	Overrolling of particles is a main contributor to damage of the raceways and could lead to a degredation of the reliability of the raceway
Internal radial clearance and roller diameter	Direct influence on loading situation and contact stress. (see also Contact stress)
Axial clearance and roller length	Direct influence on loading situation and contact stress (see also Contact stress)
Cage pocket clearance	Direct influence on loading situation and contact stress. (see also Contact stress)
Osculation	Impact on full contact / edge contact (see also Roller raceway full contact & truncation)
Material and material cleanliness and composition	Material has high influence on fatigue limit and fracture toughness but is in general not freely selectable. It is not within the scope of this project to fully characterize the impact of all different characteristics that the selected material may impact with regard to bearing reliability

Parameter	Rationale
	and flaw tolerance. The material cleanliness (melt quality) defines amount of potential crack initiation locations. The material composition has an influence on microstructure and potential crack initiation locations
Hardness	Hardness has direct influence on mechanical properties of the steel and can be contributor to cracks or spalling
Case hardening depth	Mechanical properties of the steel are changing at end of hardening zone and can influence the flaw tolerance
Residual Stress	Change in stress level could lead to decreased flaw tolerance
Specific parameters for bearings with integrated raceways	
Body stress	Generally higher stress level due to superposition of loads at the raceway compared to conventional bearings with non integrated raceways. The higher stress level increases risk of spalling and crack initiation
Material and surface treatment	The selection of the material and the corresponding heat treatment process influences the stress state and the resistance against damages and flaws
Parameters for planetary gears with integrated raceways	
Rim thickness	As demonstrated in previous research studies, rim thickness directly influences the loading and stress situation of the gear. A small rim thickness leads to an ovalization of the gear with a higher stress level and a combination of bending, shear and normal load
Contact ratio and tooth root stress (linked to body stress)	The body stress for planetary gears has a higher criticality as for integrated gears in general. The contact ratio influences the stress state and level in the gear and directly affects the body stress. For thin rimmed planetary gears, the body stress is mainly driven by the ovalization and high contact ratios can even lead to to a stress increase (reduced rim thickness due to increased dedendum height). The tooth root stress may also affect the general body stress when associated to thin rimmed planetary gears
Width of load zone (load sector) and number of rolling elements	Width of load zone (load sector) and number of rolling elements has a direct influence on stress state and level and also the amount of ovalization of the gear. A similar effect was described for the parameter rim thickness and the axial clearance. The ovalization is mandatory for reliability and flaw tolerance

Table 1: Summary of selected design parameters with high criticality for reliability and flaw tolerance [3]

For a better understanding of the dependencies of the presented parameters, a flow diagram was created (see Figure 1). All parameters have a common contribution to the overall stress state of the bearing components based on the body stress, the residual stress and the contact stress.

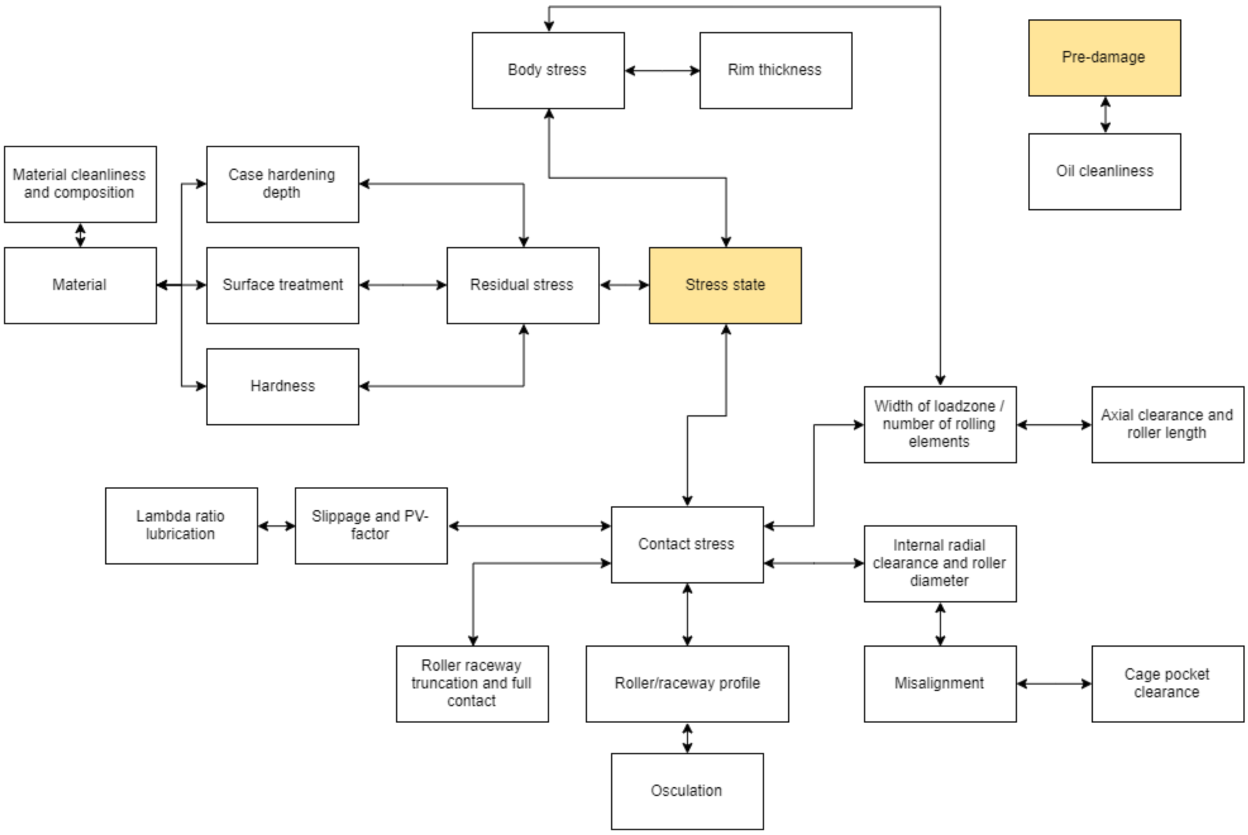

Figure 1: Interaction of critical parameters [3]

The parameter „oil cleanliness" is included in Figure 1, but it is not seen as a typical design parameter and does not directly contribute to the stress state. Therefore, it is not connected to the other parameters. Nevertheless, it will be used in the following tests in form of adequate pre-damage. The oil cleanliness has a particularity in this case as it increases the risk of crack initiation due to particle overrolling and indentations (pre-damage) on the raceway surface. The oil cleanliness is directly linked to the contamination of the oil with particles and will be therefore also considered in the following chapters. A more detailed description of this pre-damage and why it is introduced for testing will be given in chapter 3.

3. Methodology

Based on the presented hypothesis and the parameters in Figure 1, the methodology approach will be evaluated and defined within the following chapters. The methodology description will be used to create a base for the definition of the test plan and to describe the main procedure for the tasks 3 to 5.

3.1 Task 3 / Task 4

Tasks 3 and 4 are part of stream 2 of the project, containing the definition of the test plan (D2-3 and D2-6), the test report together with the evaluation of results (D2-7) and the testing phase itself. The following chapter will give an overview of the methodology of determining design limitations and developing a sufficient reliability level in order to reduce the risk of failures in a helicopter main gearbox.

3.1.1 Engineering background and assumptions

To have a common understanding of the baseline for the methodology evaluation and definition within this report, some general points have to be stated before it is possible to go into detail for the methodology of tasks 3 and 4. The complex load situation of an integrated bearing raceway and a potential failure scenario with a damage hypothesis was already given in [3]. In this case, it was illustrated for an integrated bearing raceway on a planetary gear. The damage hypothesis shows that the crack is caused by a particle overrolling and was then driven by the alternating bending load (ovalization). With the content of [3], the field experience of the ZF group and the public documents of research investigations, the following hypothesis can be claimed for bearings with integrated raceways to be used as a baseline for the further investigations:

Hypothesis:

1. In the case of a pure rolling contact load, an initiation of a crack with a finite depth may occur.
    a. Comparison of damage mechanisms of bearings in ISO 15243 and D1-1 (see bibliography)
        > Crack growth ends at a finite depth because the stress, initiated by the rolling contact, as well has a finite depth.
        > As it can be found in ISO 15243, a crack typically will lead to a pitting damage
    b. Crack growth towards the surface is known for “single load”-situation. A crack growth into the material for a “single load”-situation is known in combination with a second driver (e.g. tight press fit).
2. Without a complex load situation that is present for example in a planetary gear, there will be no further crack growth under a single load of the rolling contact.
3. Only under the complex load situation (e.g. alternating bending load), a crack propagation into the material is possible and has to be considered.

Although bearings with integrated raceways are state of the art and have been used for several years, the evaluation of critical failure scenarios, considering the combination of influencing design parameters, remains a difficult task, as mentioned in [3]. A possible way of getting a deeper understanding of the dependencies and influences is to prove the given hypothesis. To do so, the evaluation approach can be divided into three sub-phases:

- Phase I.1: Crack initiation (from a surface defect to the initiation of a crack)
- Phase I.2: Crack initiation (crack network grows and propagates but only to a limited depth)
- Phase II: Crack propagation (crack propagation because of additional loading by complex load situation)

This phases help to evaluate the overall failure mechanism and to validate the hypothesis (given in chapter 3.1.1) by three simplified steps. The phases and its content will be described in detail during the following chapters, looking at the parameter selection and the general approach for testing and simulation.

3.1.2 Selection of parameters

An overview of the priorized parameters, based on the criticality level "high" and [3], was presented in Table 1. With the help of the hypothesis and with regard to the introduced phases, a selection of the parameters with the highest level of contribution was made, to reduce the listed parameters to an useful and manageable number of parameters for testing. Looking at Figure 1, it becomes clear that all of the parameters are related to the contact stress, the body stress and the residual stress. Therefore, the residual stress and the contact stress were selected for the first phase of testing (phases I.1 and I.2) and the body stress for phase II of testing as one of the main parameters.

As the case hardening depth and the hardness have a direct influence on the profile of the residual stress and the stress state, this parameters will be taken into account, too. In comparison to other possible parameters, they can be changed without changing the geometry of the specimens itself and introducing influences on the results driven by geometrical changes (e.g. roller profile). In addition to these parameters and in combination with the residual stress curve, there is not extensive research demonstrating its influence on crack behavior. Current parameter restrictions are usually based on manufacturing related reasons.

Moreover, two different material combinations (nitrided and case carburized raceways) will be used to evaluate a possible impact of different material properties (e.g. ΔK_{th} threshold value).

As already mentioned in chapter 2, the oil cleanliness will influence reliability of bearing raceways, although it is not declared and considered a typical design parameter.

According to ZFL and bearing manufacturers, there is no reasonable design parameter limitation that will completely avoid damages (e.g. indents) arising directly from debris circulating in the transmission. Bearing designs should therefore be tolerant to such types of damages. In order to evaluate the damage tolerance of bearings with integrated races, ZFL proposal is to create relatively severe pre-damage on the samples to be evaluated. Oil cleanliness will therefore be directly covered by this damage tolerance evaluation and will be considered a 'fixed parameter' later in this report.

The selected defect size will not be changed during testing to avoid the introduction of additional influencing factors on the crack initiation and propagation by evaluating the other selected parameters. Therefore, the selected defect will be used for all of the specimen in the same manner. This gives the opportunity for a common and well defined starting point for all of the tests by introducing a reliable crack initiation mechanism and draw the focus of the evaluation on factors influencing the critical crack propagation. The evaluation of different defect sizes and shapes will not be part of this evaluation, as it will not change the general influence of the selected parameters on the crack growth phase (according to crack propagation theory), which is the primary objective of the planned evaluations. Nevertheless, the variation of selected parameters in the presence of damage will provide information on reliability level based on the influence of those parameters in the crack initiation phase.

For phase II of testing, the selected parameters will be fixed based on one baseline configuration. As mentioned above, the body stress (complex load situation) will be used and evaluated in order to prove the hypothesis (see chapter 3.1.1) and the statement that the complex load should be one of the main drivers for a critical crack propagation. Based on the results, limitations can be set for the component or raceway stress amplitude, which can finally be used for limitation of several other parameters of Figure 1 (e.g. rim thickness, width of load zone).

Table 2 and Table 3 give an overview of the parameters with regard to crack initiation for the phases I.1 and I.2 and crack propagation for phase II.

For internal reasons, the parameters were also sorted by the test capacity and experience to be taken into account for the planning and preparation of the tests. Parameters which are fixed during testing are marked in

green and variable parameters (e.g. different parameter levels will be tested) are highlighted in red. Further information can be found in chapter 3.1.4.
Some of the parameters presented in Table 2 and Table 3 have been excluded from the test plan, as specific limitations are already available (e.g. see Table 4). However, this data makes no specific consideration for damage tolerance. Another reason for the exclusion of some parameters is the fact that they primarily influence higher level parameters, as presented in Figure 1 (e.g. roundness, roughness, profiles, and clearance affect contact stress, whereas rim thickness is linked to body stress (see also the categories in Table 2 and Table 3)).

Priorization of design parameter for testing according to crack initiation phase I

	Parameter categories			
Test capacity & experience	**Contact stress**	**Contact stress / Body stress**	**Body stress**	**Residual stress**
1 (high)	Contact pressure			Material
	Lambda ratio lubrication			
2	Roller raceway truncation and full contact	Axial clearance and roller length	Rim thickness	Surface treatment
	Roller / raceway profile			Case hardening depth
	Osculation	Width of loaded zone (load sector) and number of rolling elements		
	Internal radial clearance and roller diameter			
	Contact angle			
3	Misalignment			Hardness
	Raceway / roller roughness			Residual stress
4 (low)	Slippage and P.V.-factor		Contact ratio and tooth root stress	
	Cage pocket clearance		Body stress (e.g. complex load)	
	Oil cleanliness			

	chosen key design parameter
xxx	fixed
xxx	variable

Table 2: Priorization of the parameter to be analyzed for crack initiation

Priorization of design parameter for testing according to crack propagation phase II

	Parameter categories			
Test capacity & experience	**Contact stress**	**Contact stress / Body stress**	**Body stress**	**Residual stress**
1 (high)	Contact pressure			Material
	Lambda ratio lubrication			
2	Roller raceway truncation and full contact	Axial clearance and roller length	Rim thickness	Surface treatment
	Roller / raceway profile			Case hardening depth
	Osculation	Width of loaded zone (load sector) and number of rolling elements		
	Internal radial clearance and roller diameter			
	Contact angle			
3	Misalignment			Hardness
	Raceway / roller roughness			Residual stress
4 (low)	Slippage and P.V.-factor		Contact ratio and tooth root stress	
	Cage pocket clearance		Body stress (e.g. complex load)	
	Oil cleanliness			

	chosen key design parameter
xxx	fixed
xxx	variable

Table 3: Priorization of the parameter to be analyzed for crack propagation

SRB/CRB		Comments
Tightening Hoop Stress	Case hardened steels ~around 250 MPa (function of steel thoughness) Through hardened steels : max 200MPa	
Contact Stress	Below 1600 MPa in nominal condition Below 2200 - 2400 MPa in max conditions	Highly depends on final application and duty cycle partition
Misalignment	Misalignment until full contact / edge contact	
Oil flow	NA	Calculated on the application from the bearing estimated power losses and the oil in-oil out temperature variation
Internal radial clearance	(0.015 to 0.22 mm) ; Internal radial clearance value should guarantee that, with the max ring deformation, the loading zone angle is below 160-180°	
Axial clearance	CRB : linked to roller geometry and skewing risk SRB : depends on radial clearance, contact angle, skewing risk	
Cage pocket clearance	(0.13-0.45 mm) : to avoid fatigue due to roller skewing	
Osculation	(0.50-0.59) : to avoid full contact	
Contact angle	(8 to 18°) : to optimize pressure	
Roller length (typical length to radius ratio)	Length/Diameter superior or equal to 1 Length/Diameter max ~ 1.25	
Roller diameter roughness	0.05 to 0.1 µm	Values could be limited by the manufacturing process
Roller face roughness	0.15 to 0.4 µm (standard 0.2 µm)	
Cage landing clearance	0.05 to 1 mm	
Ring raceway roundness	0.00075 to 0.001 mm	
Ring raceway roughness	0.08 to 0.2 µm	Values could be limited by the manufacturing process
Roughness of cage piloting surface	0.4 µm	
Hardness	Surface hardness : (630) 650HV to 850HV (up to 1100HV for M50NiL nitrided)	
Case-hardening depth	Nitrided steels : from 0.5 to 0.9 mm (HVcore+100) Carburized steels : from 0.3 to 1.6 mm at 550HV	
Residual stress	Surface : -400 to -1000 MPa (-1200MPa for M50NiL nitrided) Case-hardened layer : -200 to -400 Mpa	

Table 4: Typical design parameter limitations [5]

3.1.3 Test campaign and dedicated test benches

As presented in chapter 3.1.2, seven main parameters were selected for further evaluation within the phases I.1, I.2 and II, to study their influence on crack initiation and propagation. The aim of the tests is to define adequate design parameter limitations to improve reliability of bearings with integrated raceways. To do so, two different test campaigns will be carried out in parallel, based on the mentioned parameters. One of the test campaigns will be done on a simplified bearing test bench as illustrated in Figure 2 and Figure 3. This test bench has existed since 2011 and was used in six different previous test campaigns, accumulating more than 3500 hours.

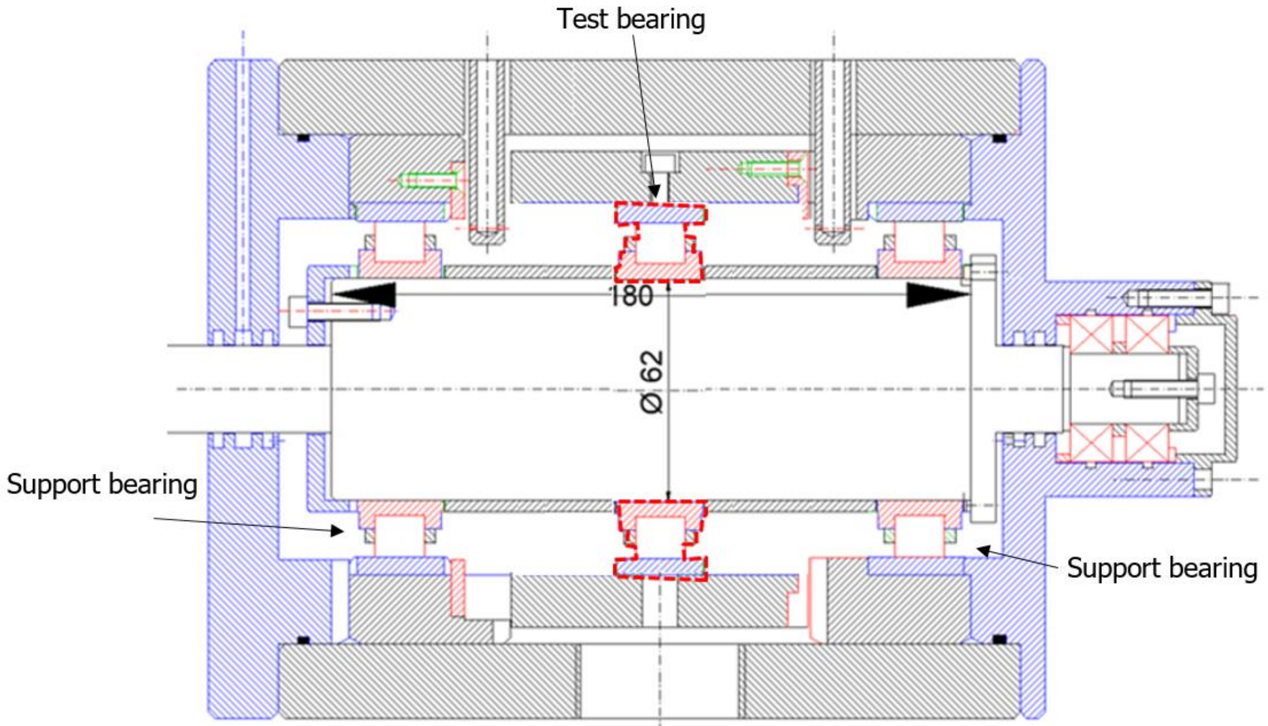

Figure 2: Test bench #1

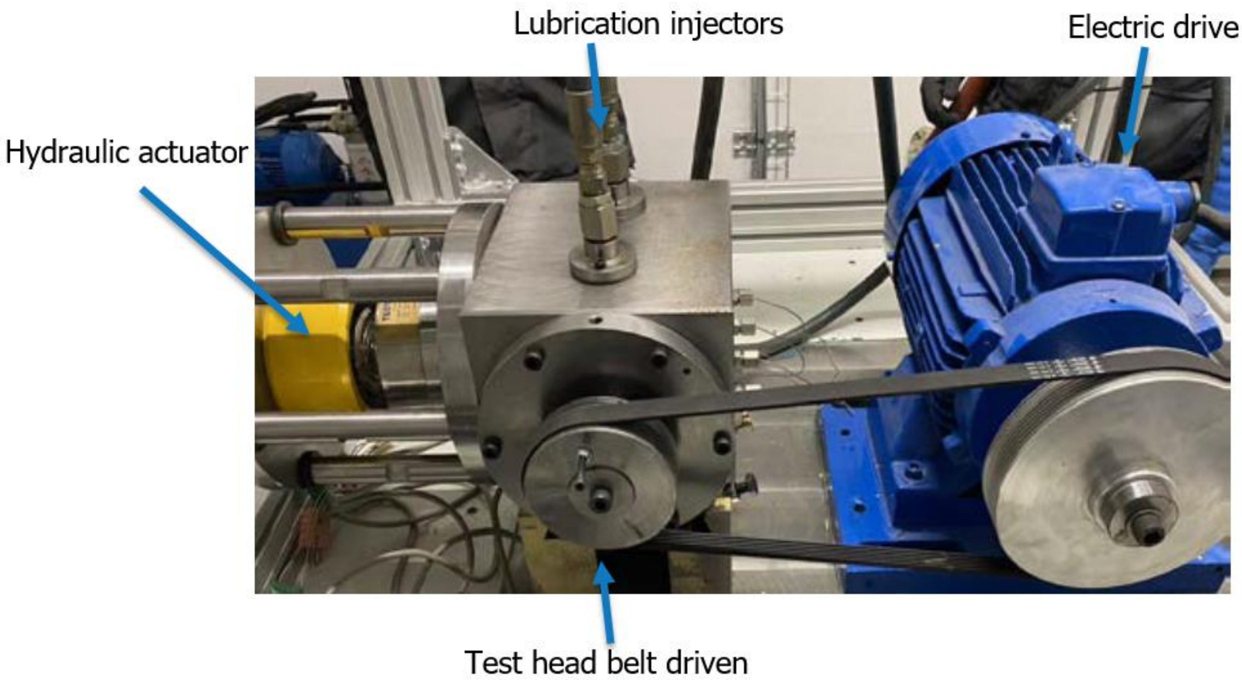

Figure 3: Actuator and drive of test bench #1

The test bench consists of a rotational shaft equipped with three bearings. Two of the bearings are support bearings, the one in the middle is the test bearing. A single test bearing is necessary to ensure a safe detection of spalling on the raceway with the help of vibration sensors and to ensure a good behavior of the shaft under high load. The test bearing to be used is a well proven CRB demonstrator bearing (see Annex B). The required roller profile to avoid roller corner contact is limiting the maximum achieveable contact pressure level of 2400

MPa for this test setup. To reach this contact pressure level, a radial force of 30 to 35 kN is required (see Figure 4). Higher contact pressure levels are manageable, but need geometrical adjustments of the specimens.

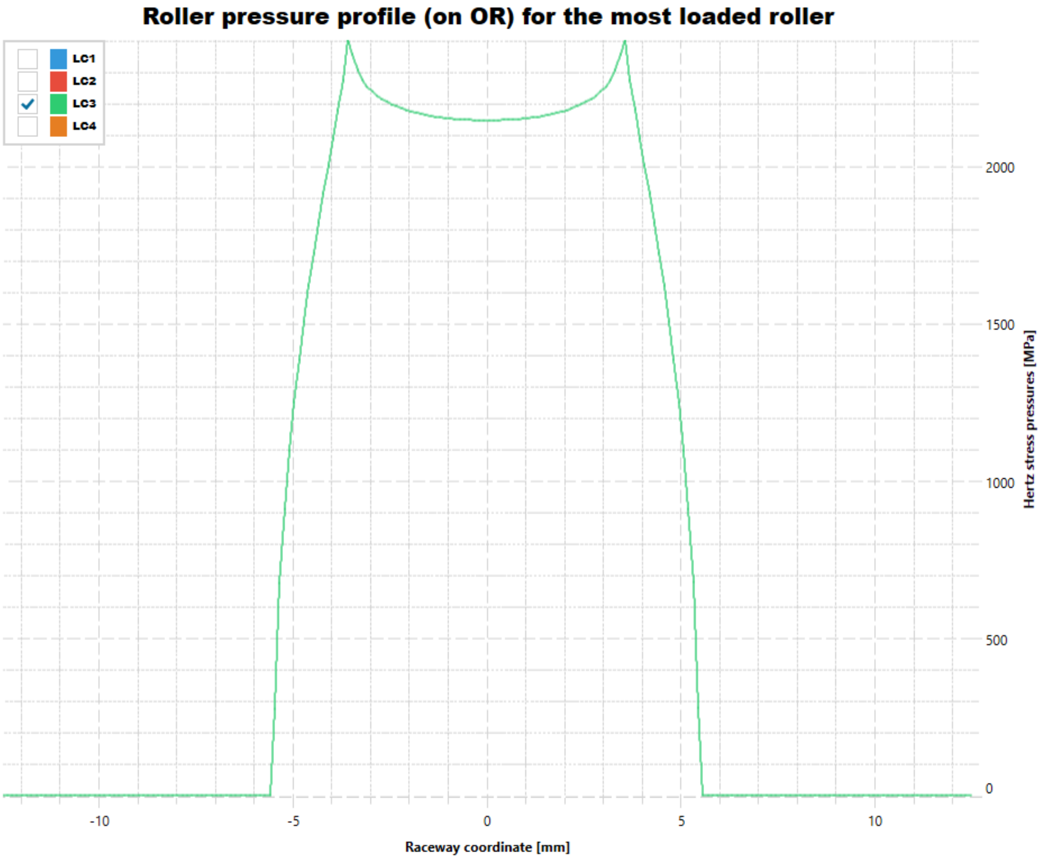

Figure 4: Roller pressure profile (max. 2,4 GPa)

The rotational shaft is driven by a belt and an electric engine. The bearings are lubricated with two injectors, mounted at the top of the test head. In addition, a hydraulic actuator is mounted on the test head, applying a radial force range of 70 kN to the test bearing. This test is intended to evaluate the influence of the parameters focusing on the raceway on the outer ring and material combinations of typical bearing materials.

The the other test campaign will be carried out on a second test bench with focus on the inner raceway and material combinations with typical shaft/gear materials. Figure 5 shows an illustration of the test bench. For this project, the test specimen and the specimen holder will be slightly adapated. The test bench has beenin use since 2010 and is well known due to recent projects (see Table 5).

Year	Project	Topic
2010-2014	FVA 504	Rolling bearing fatigue with mixed friction depending on the lubricant
2012-2014	DFG SPP 1551	Increased rolling strength and friction reduction for rolling bearings and constant velocity joints through innovative hard machining
2013-2016	FVA 705 I	Determination of operating limits of radially preloaded cylindrical roller bearings
2017-2021	SFB 1153, C3	Complex hybrid material areas with high fatigue strength subjected to rolling, torsional and circumferential bending stresses

Table 5: Recent projects on test bench #2

The test bench is capable of a heated lubrication circuit, including a filter system and is able to monitor temperature and vibrations levels, as well as the oil flow, speed and radial force.

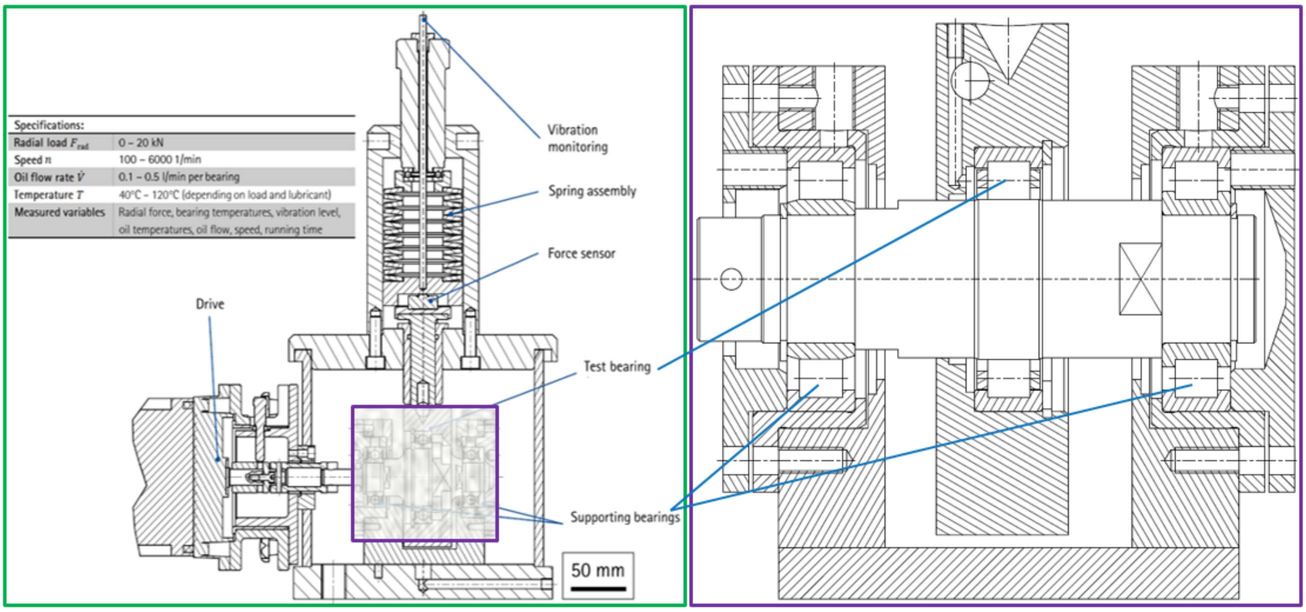

Figure 5: Test bench #2

Test bench #2 consists of two support bearings and the test bearing in the middle (see Annex D) with an integrated raceway on the shaft specimen. The basic shaft specimen is shown in Annex B. The adaption of the specimen for phase II of testing (see also complex load situation in 3.1.4) is also shown in Annex B. The test bearing type (RNU206) is well known from other research projects (e.g. FVA 798, FVA 504, FVA 863 I and FVA 541) and was chosen based on good experience with this type of bearing. A radial force can be introduced by the spring assembly pushing on the test bearing with a maximum force of 20 kN. At the maximum radial load of 20 kN and in combination with the bearing clearance CN, a maximum roller load of 7810 N will be present. In total, five rollers will carry the introduced load in this case (see Figure 6). A higher roller load is theoretically possible with a higher bearing clearance.

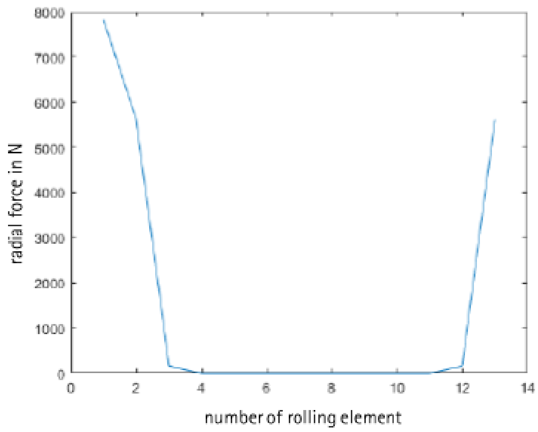

Figure 6: Radial force of rolling elements

For this load case, a maximum Hertzian pressure of 2811 MPa is achievable, as shown in Figure 7.

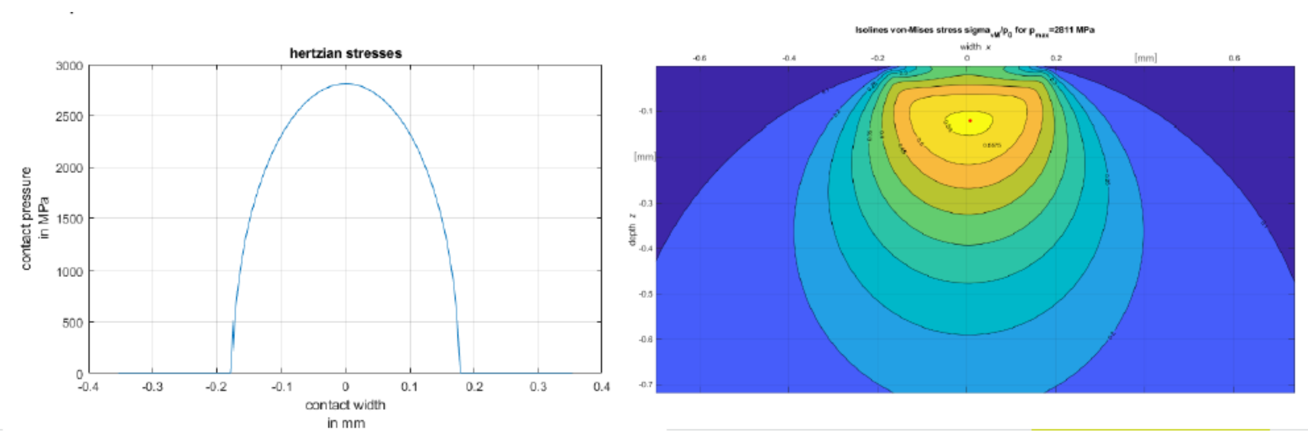

Figure 7: Calculation of Hertzian pressure for test stand #2 at 20 kN

The general procedure for the two test campaigns will be identical and can be described based on the three defined phases and the procedure illustrated in chapter 3.1.4.

3.1.4 Approach and procedure

For phase I.1 of testing, a representative defect size and shape will be defined based on typical raceway damages known from service and experience from previous testing campaigns in order to raise the likelihood for crack initiation. This artificial damages are necessary in order to reach a crack initiation during testing. Without them and under normal loading conditions of the test (e.g. limited contact pressure and bearing load according to design limits), experience from other test campaigns has shown that no crack initiation will happen within an economical period of testing time. Moreover, the focus of the test campaign is planned to start at the point where the crack is already initiated with a certain length. The selected pre-damage will be introduced with a specific tool on the raceway of the specimens (see Figure 8), whereas several indentations will be placed over different load zones around the circumference of the specimen.

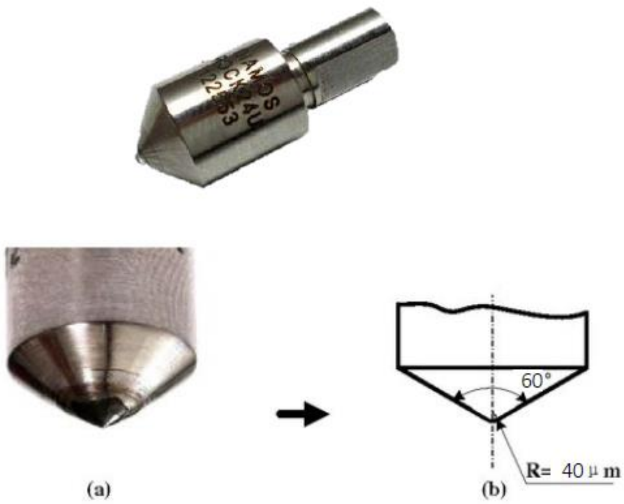

Figure 8: Indenter for test campaign

In combination with a weight of 10 kg, it will create indentations with a radius of ~100 µm, a depth of ~37 µm and a shoulder height >6 µm (see also Annex C).

Phase I.1 of testing focuses on the variation of contact pressure, whereas the other parameter (e.g. hardness, residual stress and case hardening depth) will be adjusted and fixed according to predefined baseline values. The baseline values are under investigation and will be determined by adequate measures (e.g. x-ray fine structure analysis, experience from series production).

For the contact pressure evaluation, three different levels will be tested and their influence on the crack initiation, depth and shape will be investigated. Separate simulations in advance of the test campaign will be made, to identify the required radial force and test bench setup for the selected contact pressure level (e.g. 1500 MPa or 2400 MPa). The final test bench setup will be given within the final test report. The contact pressure levels will be selected in accordance with typical bearing applications. The goal is to validate the hypothesis, that no critical crack growth will occur under pure rolling contact without an additional second driver (see also hypothesis in chapter 3.1.1) under consideration of the selected bearing and shaft materials. If no spalling will be detected, the tests shall be carried out until a total number of 200.000.000 cycles on each defect. This number is based on the experience from other similar test campaigns and should represent a sufficient running time to evaluate impacts of the selected parameters. During testing, the first detection of spalling on the raceway is important and will be detected with the help of vibration sensors and regularly inspection intervals. It is planned to stop the test one hour after first detection of a spalling event (to be finalized within final test report).

To ensure a sufficient level of reproducibility, 3 specimens for each contact pressure level will be tested.

The general test information and target values for phase I.1 of testing are summarized in Figure 9 and Table 6.

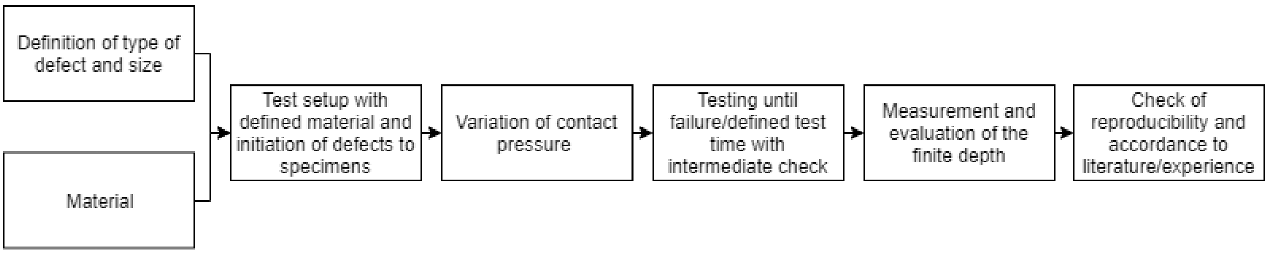

Figure 9: Procedure for phase I.1 of testing

Phase I-1	Crack initiation	From surface defect to the initiation of a crack
	Pre-damage	Predefined indent sizes: critical (quick spalling initiation) Create a line with several indents on the raceway
	Lambda value / Boundary conditions	Lambda > 3 to avoid lubrication impact on the test Speed, temperature, oil type to be chosen according typical MGB application (TBD)
	Contact pressure level	3 levels to be tested e.g.: Minimum: 1500 MPa Mean: 1800 MPa Maximum: 2400 MPa
	Materials	**Test bench #1:** Material variation only on the outer ring. M50Nil 32CDV13 Inner ring: Only 1 material (M50/100C6) Rolling Element: only 1 material - M50 **Test bench #2:** Rolling element material: M50 Shaft material: 16NCD13 (alternative: 15CrNi6 / 9310 / L9201) and 32CDV13
	Repetition	Minimum 3 repetitions to constitute a trend
	Total number of samples per test bench	3 (contact pressure) x 2 (material) x 3 (repetition) = 18
	Suspension time (number of cycle)	200 000 000 cycle on the defect Maximum time to spall
	Test stop criteria	Detection of the first spall is important: T1 T1 + 1 hour (few mm of spalling): stop of the test Retex: SuperPuma - crack from a small spall (some mm)
	Spall detection	Variation of vibration level / regular inspection intervals

Table 6: Test information phase I.1

Phase I.2 of the test campaign will be continued on the two selected test benches with new specimens. No change will be made to the boundary conditions and the introduced pre-damages. The tests will be done for all of the selected material combinations similar to phase I.1. The focus for this phase is on the variation of the hardness, residual stress and the case hardening depth, in order to evaluate their influence on the crack initiation, depth and shape. To do so, a certain contact pressure level will be defined and fixed in advance, based on the results of phase I.1. A reduced parameter level compared to the baseline (see phase I.1 of testing) of the hardness, residual stress and case hardening depth will then be evaluated. The reduced levels will be defined based on achievable manufacturing limits. These limits are currently under investigation and the final values will be provided within the final test plan.

The main procedure and general information of this test phase are summarized in Figure 10 and Table 7. The ranges of the parameters are currently not representative and shall only give an general idea of the methodology. As mentioned above, representative values are under investigation and will be given within the final test plan before start of the testing campaign. It is planned to test the parameter values as a first step only at two levels (e.g. baseline level and reduced level, see Table 7) as it is common for a DoE (design of experiments) approach.

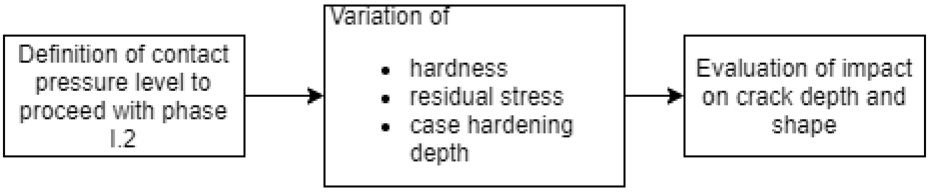

Figure 10: Procedure for phase I.2 of testing

Phase I-2	Crack initiation	Crack network grows and propagates but to a limit depth
	Pre-damage	Same as Phase I-1
	Lambda value / Boundary conditions	Same as Phase I-1
	Contact pressure level	Defined acc. to Phase I-1
	Materials	Same as Phase I-1
	Surface Hardness	2 levels (depending on prototypes, e.g. 58 HRC to 63 HRC) -Baseline level -Reduced level
	Residual stresses	2 levels (depending on prototypes - process uncertainty) TBD max compressive stress and TBD max tensile stress (residual stress profile)
	Case hardening depth (TBD HRC at TBD depth)	2 levels (depending on prototypes - process uncertainty) -Baseline level (e.g. 1 mm) -Reduced level (e.g. 0,15 mm)
	Repetition	Minimum 3 repetitions to constitute a trend
	Total number of samples per test bench	1 x (Contact pressure baseline level) x 3 (parameter reduced level) x 2 (material) x 3 (repetition) = 18
	Suspension time (number of cycle)	Same as Phase I-1
	Test stop criteria	Same as Phase I-1
	Spall detection	Same as Phase I-1

Table 7: Test information phase I.2

Phase II of testing will focus on the introduction of a complex load situation and the evaluation of the impact on the crack propagation. To do so, one baseline variant from the previous tests will be selected (based on contact pressure, case hardening depth, hardness and residual stress) and applied on new specimens. The test will be carried out on both selected test benches and for the two material combinations used within the previous tests.
Due to the fact that critical crack growth in combination with a catrastrophic failure was observed in a planetary gear system with an integrated raceway (see also [3]), a representative planetary gear setup of an helicopter MGB application (not specially corresponding to the design presented in [3]) was created and used to get an estimation of the necessary load amplitude for the complex load situation. Therfore, a simplified FE model was created for a thin rimmed planetary gear with typical boundary conditions and loads (see Figure 11) as a representative real case.

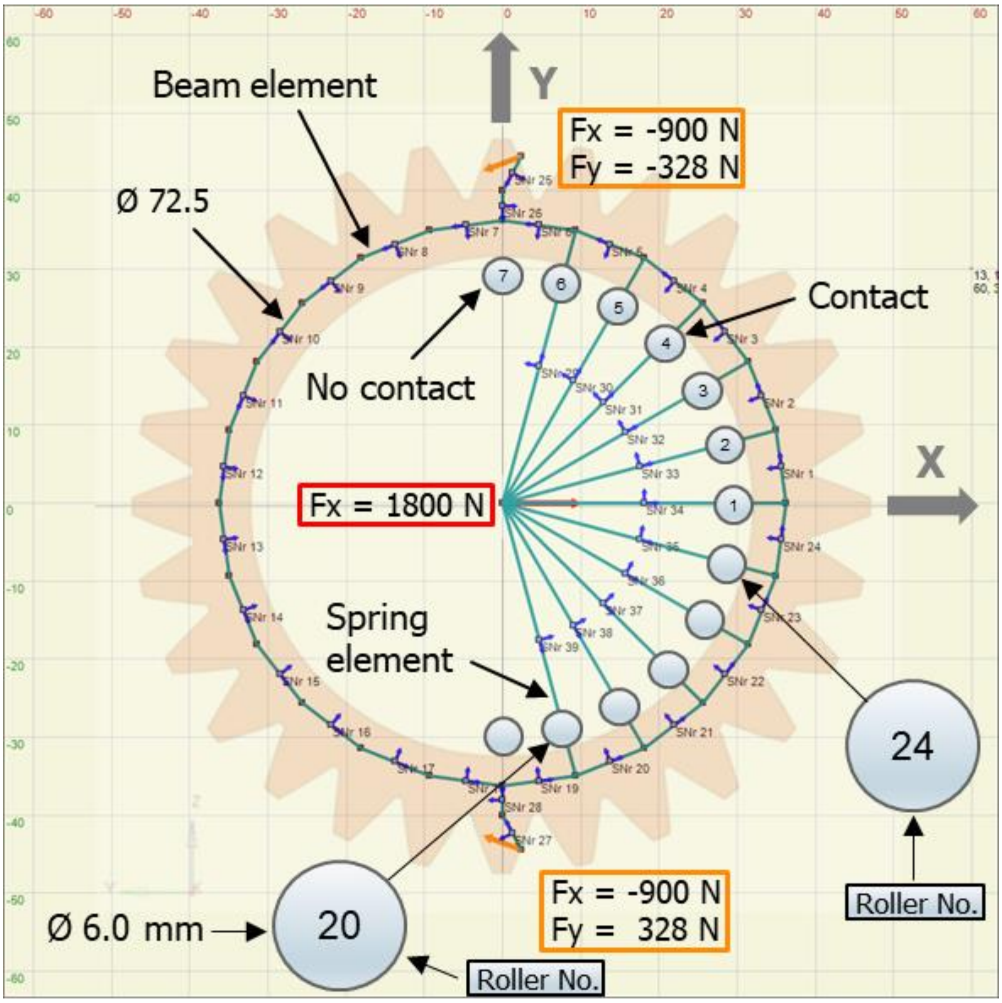

Figure 11: Simplified 1D model of planetary gear

Based on the given FE-model, the following stress distribution was calculated (see Figure 12 and Equation 1 - Equation 2), resulting in a stress amplitude of approximately 70 MPa. This amplitude will be used as an orientation for the implementation of the complex load situation for test bench #1 and #2. This value is an example and first approach based on the currently available information. Under consideration of the ongoing FE crack simulations (for details see chapter 3.3), this value has to be validated and updated if necessary. The contact pressure is not considered in this calculation. As the test benches will be selected and test specimens ordered before having the results of the simulations afore mentioned, the capacity to reach higher stresses, if found nececarry based on simulation to produce crack propagation, will be ensured by adjusting some of the specimen characteristics. This will be done by e.g. notch dimensions on bench #1 or similar adjustments for the test bench #2.

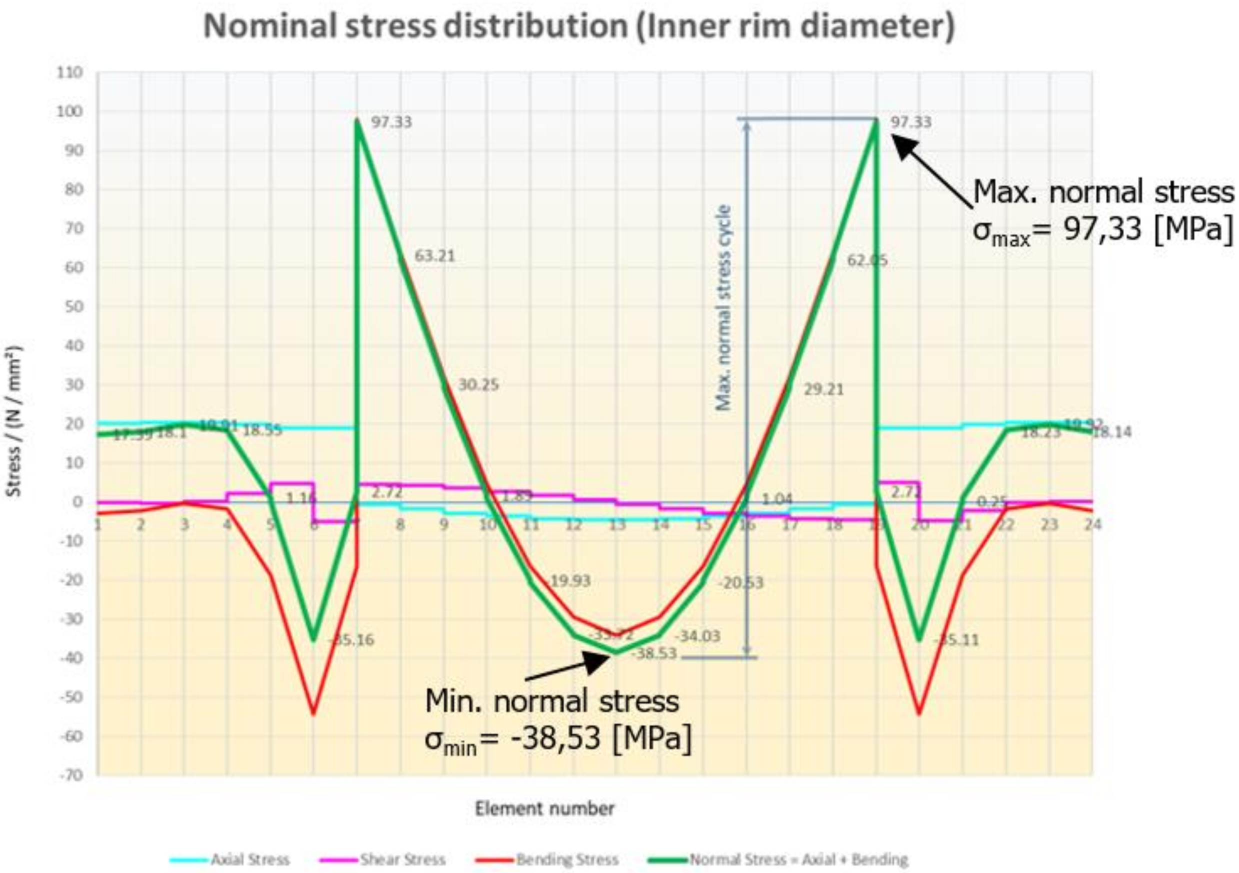

Figure 12: Stress distribution for simplified planetary gear

$$\Delta\sigma = (\sigma_{max} - \sigma_{min}) = 135{,}86\ [MPa]$$

Equation 1: Stress range

$$\sigma_a = \frac{1}{2} \cdot \Delta\sigma = 67{,}93\ [MPa]$$

Equation 2: Stress amplitude

To introduce the complex load situation on test bench #1, the specimen will be adjusted by a notch/groove at the outer ring before the final carburizing/nitriding process so that the outer ring is able to bend under the roller load (see Figure 13).

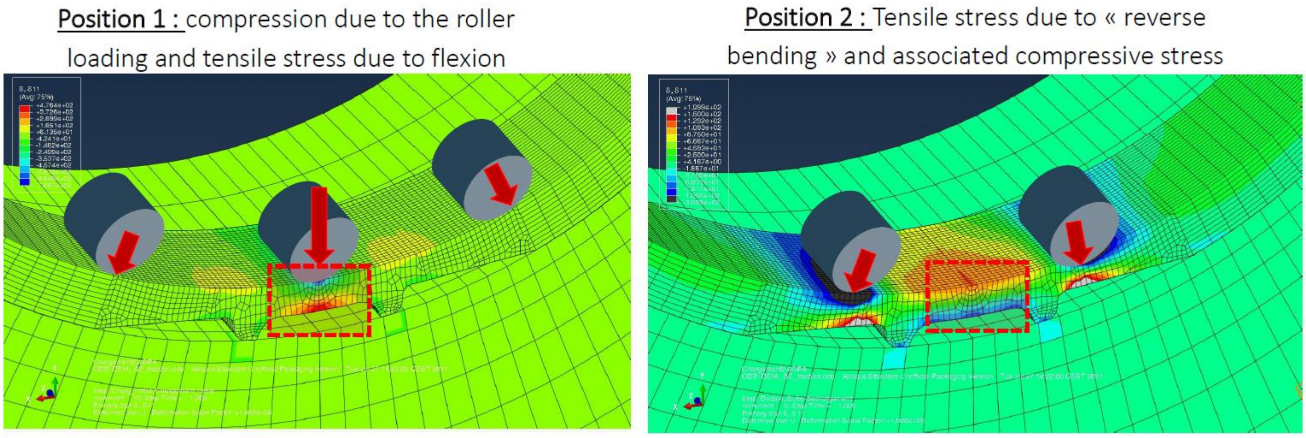

Figure 13: FE-analysis of complex load for test bench #1

The notches will be manufactured by electronical discharge machining (EDM) and can be applied and adapted just before final heat treatment and assembly of the specimen with a short lead time. This offers ample flexibility to adapt the complex load in a late stage of the test campaign.
A first simulation was carried out to evaluate possible stress ranges (see Figure 14). Figure 14 shows the simplified stress profile. The compressive stress on the raceway surface is a superposition of the contact pressure of the rolling element and the bending stress. The tensile stress is free of the rolling contact load. Compared to the necessary stress amplitude of the representative FE simulation (see Figure 12), the required stress amplitude can be said to be achievable. Changes in the notch size must be aligned with the detailed carburizing/nitriding process, especially due to the limited thickness of the bearing ring. Higher stress amplitudes would be possible by changing the notch geometry and depth.

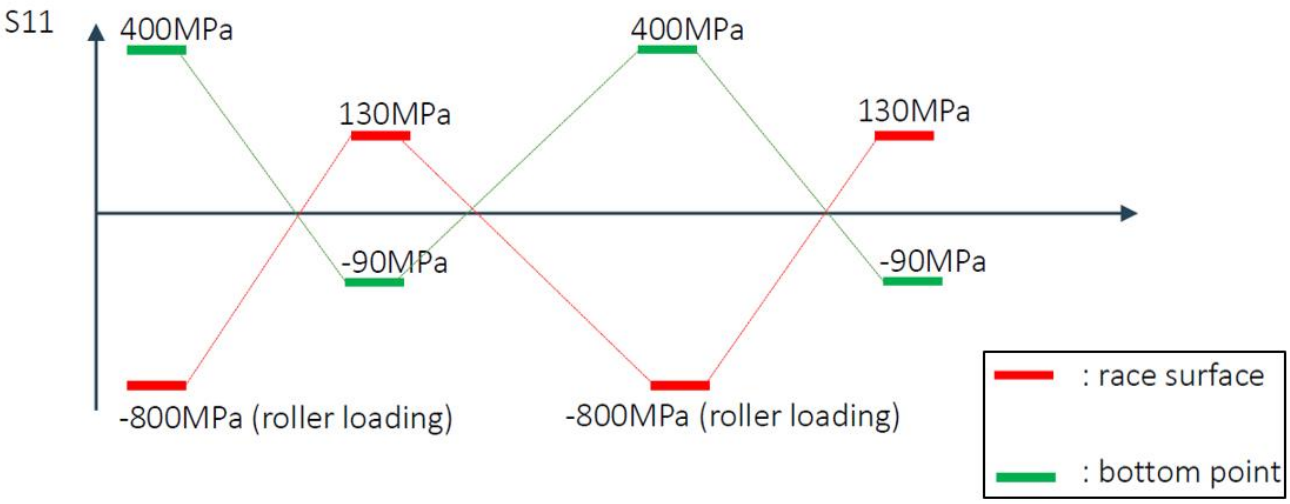

Figure 14: Example of stress profile complex load situation test bench #1 evaluated by simulation

For test bench #2, the complex load situation will be introduced by a bending load on the shaft specimen, producing a certain body stress (see Figure 15; hollow shaft is not illustrated). To do so, the shaft from phase I will be replaced by a hollow shaft so that the introduced radial force applies a bending load and bending stress on the shaft (see Figure 16).

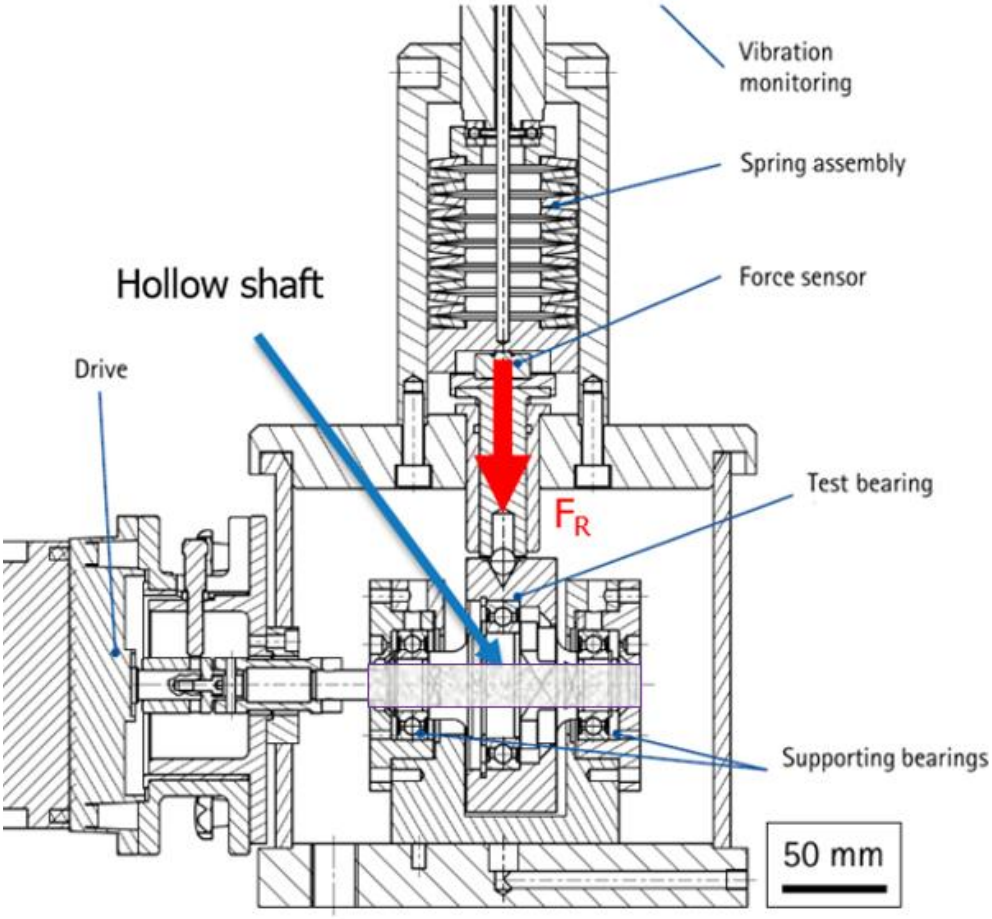

Figure 15: Complex load introduction at test bench #2

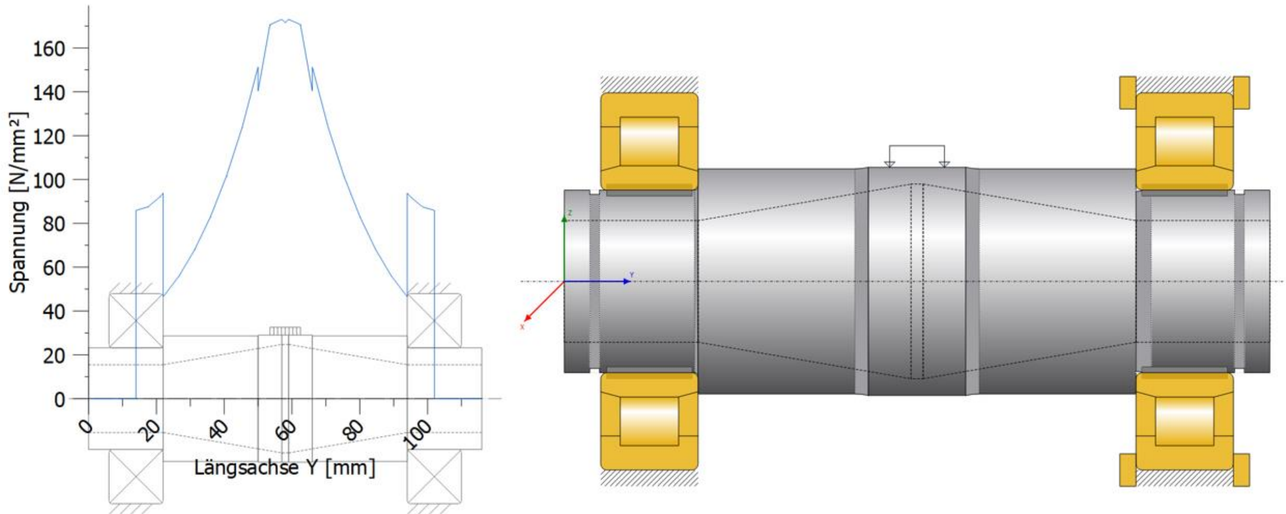

Figure 16: Bending stress profile for selected hollow shaft

Calculating the stress profile for a single point on the raceway for one full shaft rotation, a maximum amplitude of ~100 MPa (stress range of 200 MPa) will be achievable with the currently planned test setup (20 kN radial force). Larger values are possible by an adaption of the shaft specimen or setup of the test setup, which can be done in parallel of the test campaign if necessary.

Although the achievable stress range on test bench #2 is similar to the stress range at test bench #1, the complex load situation as well as the purpose of this test are different. The shaft bending creates an alternating stress in the shaft axis direction (z-direction), whereas the ovalization of the bearing ring at test bench #1 leads to an alternating stress in tangential direction. The different stress directions and materials used within this two test campaigns might lead to different conclusions for crack propagation and will gain a more general knowledge about critical crack propagation within different applications (e.g. planet gear and shaft applications).

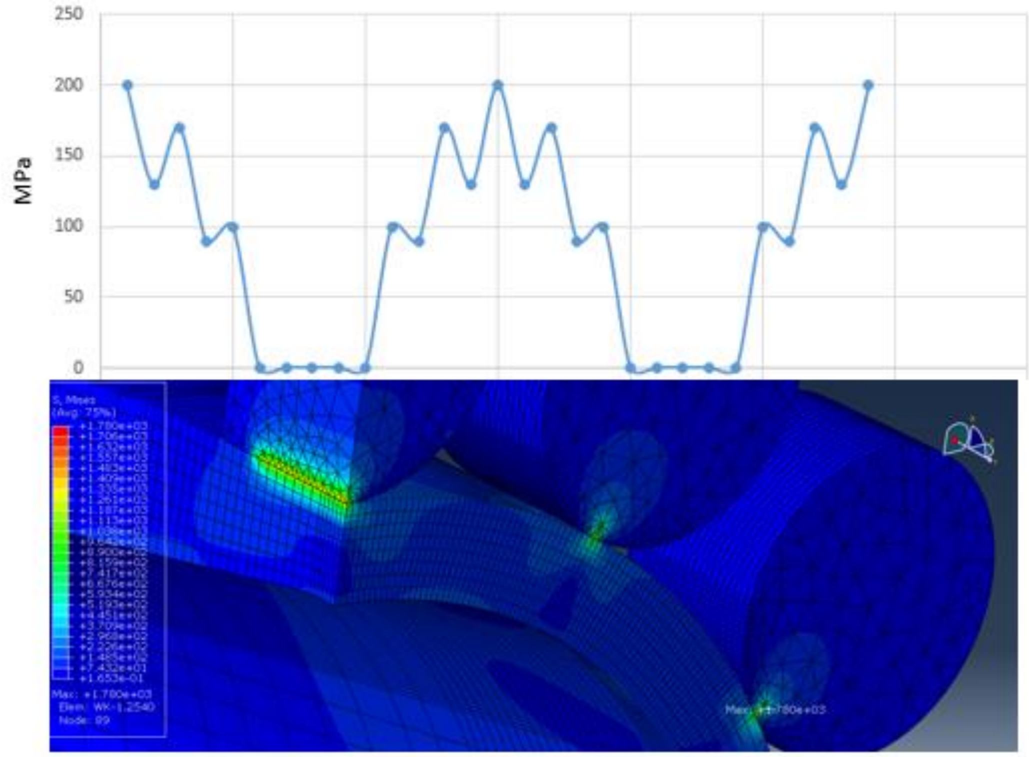

Figure 17: Simulated stress profile for single point on shaft raceway for a full cycle

The aim of this test phase is evaluating the impact of the complex load situation on the crack propagation and validating the described hypothesis for bearing applications with integrated raceways. Preliminary crack simulations (see chapter 3.3 for details) are ongoing and will be available before start of the test phase. Based on the results, the specimen and/or test bench boundary conditions can be adapted quickly (e.g. notch size, contact pressure, inner diameter of the shaft, etc.) in order to achieve a crack growth into the body and validate a sufficient and representative real case scenario. Testing and simulation will be used in combination as an iterative approach to achieve reliable results (see also 3.3 for more details). The procedure and the general information for phase II of testing are summarized in Figure 18 and Table 8.

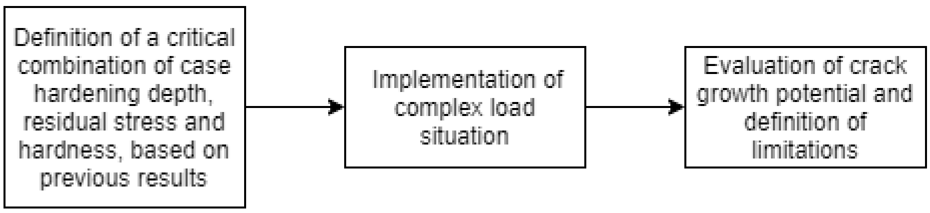

Figure 18: Procedure for phase II of testing

Phase II	Crack propagation	Crack propagation because of additional loading by complex load situation
	Pre-damage	Same as Phase I-1/I-2
	Lambda value / Boundary conditions	Same as Phase I-1
	Contact pressure level	Defined and fixed acc. to Phase I-1/Phase I-2
	Materials	Same as Phase I-1/I-2
	Surface Hardness	Defined and fixed acc. to Phase I-1/Phase I-2
	Residual stresses	Defined and fixed acc. to Phase I-1/Phase I-2
	Complex load situation	2 levels Approximately $\Delta\sigma$=136MPa stress range Reduced level
	Case hardening depth (TBD HRC at TBD depth)	Defined and fixed acc. to Phase I-1/Phase I-2
	Repetition	Minimum 3 repetitions to constitute a trend
	Total number of samples per test bench	1 (complex load situation) x 2 (material) x 3 (repetition) = 6
	Suspension time (number of cycle)	Same as Phase I-1/I-2
	Test stop criteria	Same as Phase I-1/I-2
	Spall detection	Same as Phase I-1/I-2

Table 8: Test information phase II

The evaluation of crack growth potential and definition of limitations will be done based on the test results in combination with the FE crack simulations. An iterative approach between simulation and testing will be used to ensure reliable results (see 3.3). This evaluation will be done separately for the tested applications on test bench #1 and #2 (crack growth potential on integrated raceway with deformable outer ring and crack growth potential on integrated bearing race on a shaft). To do so, the results from phase I of testing will be compared to the results of phase II of testing. Cuts of the specimens will be made (measurement of crack depth, crack angle, crack path, etc.) in order to visualize the crack propagation and to compare and correlate the results from the FE simulation with the test results.

Although the planned tests do not represent a real planetary gear system or other rotors and rotor drive system-integrated bearing applications, sufficient similarities are present (e.g. deformable outer race at test bench #1, material combinations, material properties, manufacturing processes, etc.) to ensure applicability of the test results to the aforementioned applications. Furthermore, design solutions or limitations for the selected parameters can then be proposed based on these tests and validated FE crack simulation.
A detailed description on how the parameter limit evaluation can be supported by the FE-simulation will be given within report D2-5, as soon as the FE model is validated and the simulation approach is finalized.
The required number of specimens for the described test procedure and the configuations are summarized in Table 9 exemplarily for one of the test benches. The total amount of specimens for both test campaigns is twice the given specimen quantity. The minimum quantity for each test bench to fulfill the required tests is 48 pieces. In order to have some spare specimens for potential additional tests, some more specimens per test bench are foreseen for phase II of testing (at least three per material; see also 3.2.2). Moreover, some stock pieces are foreseen for the rest of the testing phases (at least 1 for each configuration setup) to remain flexible in the case of unforeseen problems during testing. Looking at Table 9, it becomes clear that the selected parameters can be evaluated independently. To ensure that the parameter target values are achieved, accompanying samples will be manufactured and checked destructively beyond the mentioned samples per test bench.

Position	Raceway configuration				Quantity
	Material	Hardness	Hardness depth	Residual stress	
1	16NCD13 / 15CrNi6 / 9310 / L9201	A	C	E	12
2	32CDV13	A	C	E	12
3	16NCD13 / 15CrNi6 / 9310 / L9201	B	C	E	3
4	32CDV13	B	C	E	3
5	16NCD13 / 15CrNi6 / 9310 / L9201	A	D	E	3
6	32CDV13	A	D	E	3
7	16NCD13 / 15CrNi6 / 9310 / L9201	A	C	F	3
8	32CDV13	A	C	F	3
	Sum				42

Table 9: Example of required test samples for test bench 2

Hardness [HRC]:
A ~ 58
B ~ 63

Hardness depth [mm]:
C ~ 1,0 $_{+0,4}$
D ~ 0,15 $_{+0,2}$

Residual stress [MPa]:
E ~ -700
F ~ -400

Material standard:
16NCD13 – WL1.6658 /AMS 6548
9310 – AMS 6267 / AMS 6265
L9201 – ZFN L 9201
32CDV13 – AMS 6265

3.2 Task 5

Task 5 is part of stream 2 of this project, containing the analysis and evaluation of critical factors for crack initiation and crack growth with the main goal to determine crack prevention factors. The following chapter will give an overview of the methodology for determining crack prevention factors.

3.2.1 Engineering background and assumptions

Rolling contact fatigue is a special case of material fatigue. Running-in processes and interactions between plastic deformation, wear, lubricant chemistry and the accumulation of abrasion are the subject of current studies. After evaluation of available literature, the damage development of initially small cracks on rolling contact can be qualitatively described.

The crack growth occurs against the direction of the exerted frictional force, usually against the rolling direction and running approximately parallel to the surface, branching out or forming secondary cracks and then leading to surface breakouts. ZFL considers this behavior to be typical. Although this propagation pattern has been well documented through observation and experience, deviations are known that are associated with fatal consequences. In particular, these are cracks that “turn down” as they propagate and lead to a through-fracture of the component. A propagating crack in the plane with isotropic material under pure mode I loading generally follows a straight crack path. If there is a pure mode II or a mixed mode I / II stress, a deflection of the crack is observed. For the deflection from the original crack plane, many different criteria were developed. These criteria are all in accordance with the premise that mode II stress is minimized and mode I stress is maximized to provide comparable results.

The condition $\Delta KII = 0$ (stress intensity factor range at cyclic loading) is therefore also suitable as a basis for a crack deflection criterion for the calculation and prediction of the crack path under dynamic mixed-mode loading.

The main distraction criteria are:

- Maximum tangential stress criterion
- Strain energy density criterion
- Criterion of the J integral vector

There are a number of studies in which the numerical methods for simulating crack propagation have been discussed. In a typical simulation, the boundary condition for cracks is free from pressure loads. Due to the practical importance and the large number of applications, most studies mainly deal with crack propagation under tensile stress. Nevertheless, a crack can propagate under compression, as is the case with rolling contact. In general, numerical simulations of crack propagation under tensile stress are comparably simple and well proven by tests while those under compression have various difficulties, such as handling partial contact and friction.

There are only a few studies that try to predict the crack path under compressive stress and simultaneous shear in mixed mode under cyclic loading. Some of the results differ greatly from experience and observations.

It can also be noted that current calculation programs and standards with regard to the mathematical handling of pressure and shear stress cycles tend to be ambiguous.

As described above, determining the crack path under rolling contact is difficult. In addition, traditional rolling bearings have already achieved a degree of optimization so that a branching off of a surface crack into the component is seldom observed.

A change in the propagation of cracks under rolling contact may occur due to the presence of internal tensile stresses in the depth direction. Figure 19 shows an example of a residual stress distribution with residual tensile stresses of a planetary gear. From a fracture mechanical point of view it can be assumed that the internal tensile stresses exceed the compressive stresses induced by the rollover as cracks have been initiated on the surface. This can lead to crack opening and thus to an increased rate of crack growth in the direction of the depth.

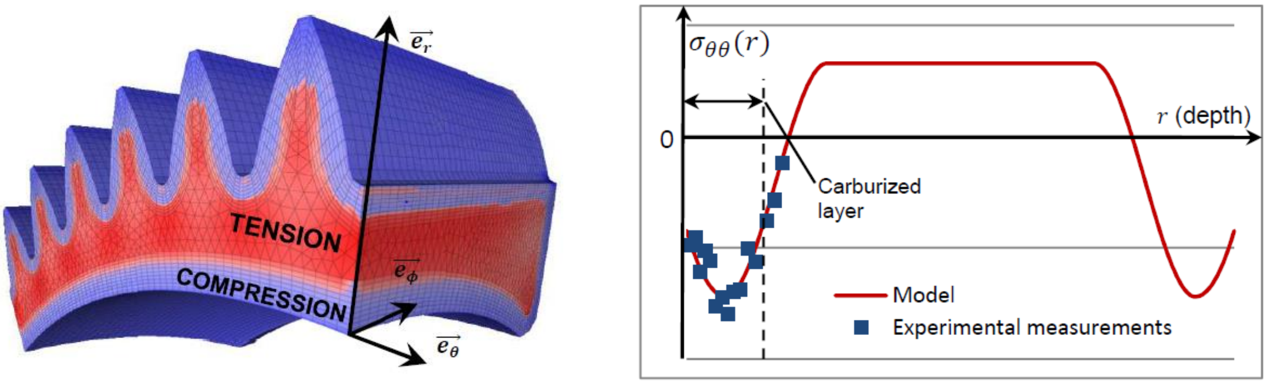

Figure 19: Residual stress distribution for the outer ring of a planetary gear [4]

3.2.2 Approach and procedure

For task 5 of this project, two separate approaches are planned in order to manage the difficulties described in chapter 3.2.1. On the one hand a numerical approach, and on the other hand a practical approach (testing). The numerical approach can be summarized by the following (for details see also 3.3):

- Creation of a 2D FE model for evaluation of crack growth based on a 2D mixed-mode load situation under consideration of rolling contact
- Development and validation of a combined simulation technique with ABAQUS and ADAPCRACK3D
- Parameter study and limit evaluation of crack angle, crack depth/length and contact pressure to get a basic understanding of a critical crack geometry
- In case valid and reliable FE results can be produced, parameter evaluation to support results of tasks 3 and 4 can be done (e.g. residual stress, case hardening depth, hardness)
- As a final step, a complex load situation will be implemented in order to validate the hypothesis of a critical crack growth in combination with a second driver

The practical approach is dependent on the results of the previous tests of tasks 3 and 4. Without the final results of these tasks, there are two possible options and ways to proceed to task 5.

- Option 1 - No critical crack growth / failure scenario can not be reproduced
    - Further investigations on a possible approach to reproduce the critical failure scenario will be done based on numerical investigations in order to find a critical parameter combination to reproduce the critical failure scenario
    - Based on the numerical results, critical parameter combination will be tested practically in order to validate numerical results
    - Finally, the results of the numerical and practical investigations will be used to conclude on appropriate design limitations by variation of the parameters until critical crack growth stops
    - As mentioned in 3.1.4, six additional specimens for each test bench will be manufactured in order to have the possibility of testing an additional parameter variation, a larger pre-damage size or a higher level of the complex load.
    - This additional tests are limited to the given test benches and the proposed specimens.

- Option 2 - Critical failure scenario will be reproduced
    - If the critical failure scenario can be reproduced, the tests will be extended with additional parameter levels to ensure a more detailed assessment of the parameter limitations.
    - Additionally, the above described numerical approach will be used to align on the parameter limitations and validate the test results by a scientific approach.

The given testing options have to be checked and updated as soon as the first results from the simulation and testing are available. The final number of additional specimens and the changes to the setup, which may be needed, will be detailed within the final test plan. The iterative approach between testing and simulation is defined in detail in chapter 3.3.

3.3 FE-crack simulations

This chapter is intended to give a more detailed view on the mentioned FE-crack simulations in chapters 3.1.4 and 3.2.2. As a reminder and synthesis of the information provided in the previous paragraphs, the FE-crack simulations are planned to be performed to:

- Adjust design parameter levels prior to performing the tests: These simulations give the opportunity to introduce changes and updates on the planned setup of the tests and the selected properties of the specimens by forecasting the crack path of the tested specimens.
- Help define design parameter limitations following tests: Correlations between tests and simulations would allow to validate the FE simulation methodologies. By achieving this, the simulations can also be used to evaluate additional parameter variations and levels, compared to the limited number of tests, to gain a more detailed view on possible design parameter limitations. In particular these simulations could be used on planetary gear designs, even if not tested initially, with the aim of identifying possible specific design parameter limitation.

The general method which is used for the simulation is based on FE-simulations with ABAQUS in combination with an evaluation in ADAPCRACK3D (see Figure 20 [10]). ADAPRACK3D can be used for 2D and 3D models either. The simulations will be performed using the following modeling hypotheses:

- **Use of software ADAPCACK3D:** ADAPCRACK3D is a numerical and automatic crack growth simulation software based on finite element method and can be used to simulate crack growth in 2D or 3D models by considering mixed-mode loading situations. The software consists of two separate modules (NETADAPT3D and NETCRACK3D, see also Figure 20), which can be included within the commercially used software ABAQUS. NETADAPT3D is responsible for the mesh generation and adaption. For each iteration of the simulation, the newly calculated coordinates of the crack front nodes are handled with a mesh adaption algorithm to accommodate the new crack front by a remeshing process at the crack front. For the mesh, tetrahedral and hexahedra elements are used for the submodel and the global model. The module NETCRACK3D will do the fracture mechanical evaluation with all the nececarry parameters (e.g. lifetime, stress intensity factor, coordinates of crack front, crack growth direction, etc.) [12]. Using ADAPCRACK3D, the domain around the growing crack is replaced by a submodel technique [11], which allows efficient crack simulation with a sufficient level of detail. In contrast to X-FEM, this enables a much better accuracy in calculation of stress intensity factors and a higher efficiency in general, which is useful for the evaluation of the rolling contact problem ([13], [14]). ADAPCRACK3D is a state of the art software (see [10], [11], [12]), which was already validated and aproved in several other projects. Similar simulations were already carried out for a rubber-sprung railway wheel with a crack under rolling contact. The simulations have shown good results [15]. Nevertheless, the simulation of rolling contact fatigue within a planetary gear system is not state of the art. It may be difficult to find a sufficient and representative level of detail within the FE model and to use the right boundary conditions (e.g. material data, friction values, etc.). The test results will help correlate and adjust the simulation.

- **Material characteristics:** For simulations performed with the aim of adjusting design parameter levels prior to performing the tests, the material characteristics will be taken from the literature and supplier databases. In addition, the software NASGRO will be purchased, to have access to a wide range of material data. These material characteristics might be re-evaluated following the correlation between simulations and tests. Within the used software, it is possible to consider material characteristics for mode I and mode II crack propagation (e.g. crack growth curves).
- **Geometry for meshing:** The nominal 3D CAD parts will be used for modeling. The indents and potential damages such as pitting/spalling that could be generated in test prior or in parallel to the crack propagation are not intended to be modeled. Only an initial crack will be introduced.
- **Initial crack:** The fracture mechanics concept always starts from a component with a technical crack ([16], [17]). Therefore, the initial crack size for the simulation will be chosen based on long cracks (≥ 0.5 mm), as the simulation of this cracks is state of the art. The simulation of short cracks (≤ 0.25 mm) is difficult, as the crack properties and characterstics change and the standard simulation techniques are no longer applicable (e.g. plastification). An initial crack angle of 30° will be chosen, as this angle is typical for cracks at a raceway under rolling contact [18]. This angle will be variated to lower values, referring to the EC225 accident experience and literature. The initial crack angle is dependent on the rolling and sliding condition of the rolling element. Based on the experience of the partners and available literature values, the crack angle and size will be variated to get an imagination of the influence of this parameters. As the first tests are done, the results from test and simulation will be compared and the final crack geometry will be defined for the further investigations.
- **Correlation and validation of the model:** The starting point of the simulation and the test is different, as the specimens are equipped with indents, which are not modelled in the simulation. The indents can be seen as an initiator for a crack, to ensure crack growth in a short period of time and at the right position during test. The correlation of the test and the simulation will be possible, after the crack reached a specific length (≥ 0.5 mm, for long cracks). First aspects to be correlated are the crack angle, the total crack depth/path and more generally the question, if the crack arrests or not. A first point of correlation will be the pure rolling contact without any additional drivers that could influence the crack propagation (test phase I – variation of contact pressure). The common experience in this case is, that cracks always tend to arrest or only grow back to the raceway surface. This should be validated and correlated during testing and simulation.
- **Evaluation of design parameter:** If initial crack parameters are found to have significant influence on simulations and/or test results, the simulation and the tests (as it is manageable within the timeframe) will focus on these parameters by variating the parameter levels in a feasible range, to define possible limitations for the design to ensure an arrest of the crack or a non critical crack growth towards the raceway surface. Within a conclusion of this project, design limitations can be provided or emphasized based on this evaluations.
- **Rolling elements to raceways loading conditions:** The contact conditions (including frictional forces) and associated pressure between the rolling elements/raceways will be the result of FE solving, considering the effect of the crack presence (i.e. not introduced as a theoretical contact based on Hertz theory). Nevertheless, it is not intended to introduce EHL effects on the contact conditions due to the lubrication. Friction will be introduced in the contact area based on the speeds of bearing elements.
- **Residual stress:** As residual stress created by thermochemical treatments is a key parameter to be studied, this parameter is intended to be introduced in the simulation. This will be done by mappingresidual stress fields to the nodes/elements of the crack simulation with the help of a pre-simulation. It can be done in the same way, as temperature fields from a thermal analysis can be mapped to a structural simulation model.
- **2D/3D FE models:** Initial simulations, and simulations requiring iterations to determine the influence of different parameters will be done based on a 2D model (see Figure 21), to reduce the number of elements

and complexity. If needed, for instance to obtain appropriate correlations or conclusions for design limitations, these simulations could be extended to 3D models (in the limit of computation capacities). It is expected that such 3D simulations would be needed to draw conclusions for applications such as planetary gears.

- **Fracture mechanics and simulation:** The fracture mechanical material properties will be included by the FORMAN-METTU equation [19]. This methodology is considered to be capable of simulating crack propagation conditions in mode I and mode II [20]. The tool NETADAPT3D will make the automatic mesh adaption, considering the geometrical changes of the cracked components due to the crack propagation. The FE-solver ABAQUS can use this mesh to do the required calculations at the crack front (strains, stresses, displacements, etc.) based on the given load data for the global and the sub-model. An example of the sub-model technique is presented in Figure 22. The fracture mechanical evaluation will be done under consideration of the MVCCI-method [21] by calculating the stress intensity factors, lifetime and crack area for the sub-model. With the help of the σ1´-criteria [8], the equivalent cyclic stress intensity factor, the kinking angle and the twisting angle can be additionally determined. As long as stable crack propagation is confirmed, load cycles and new crack front coordinates will be calculated and a new iteration step will be started with the adaption of the FE-mesh. No crack propagation will be calculated until the resulting stress intensity factors reach the applicable thresholds.
- **Simulation iterations and link to tests:** The crack simulation within this project is an iterative process, as such simulations are not perfect. As described above, the simulations will start with predefined boundary conditions (e.g. crack angle, crack length, friction force, etc.) to have a starting point for the simulations. This boundary conditions are chosen based on experience and other research projects. After the first available test results, the specimens will be examined by material cuts and the results will be reused to feed and calibrate the FE simulations in order to reach a stable and reliable crack growth and crack path prediction. As a validated simulation procedure is reached and all design parameter that have a significant influence on the crack propagation can be considered sufficiently, the simulation can be used to determine design limitations for the defined design parameters with a higher level of detail and a wider range, as it is possible within the limited testing time. Moreover, the simulation will be used to prepare the boundary conditions (e.g. complex load situation) for phase II of testing. Once the design parameters are evaluated, a final validation of this parameter changes can be done by testing to achieve the objectives of this research project.

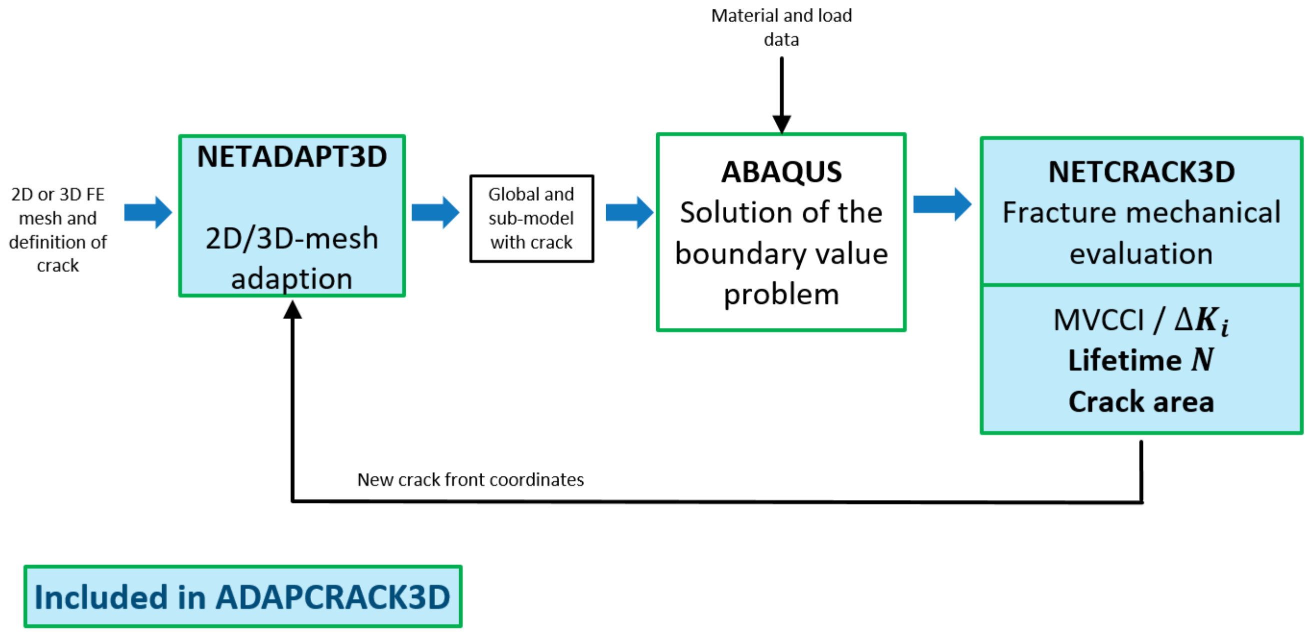

Figure 20: Example of a combination of Abaqus and ADAPCRACK3D for crack evaluation of a 2D or 3D geometry [10]

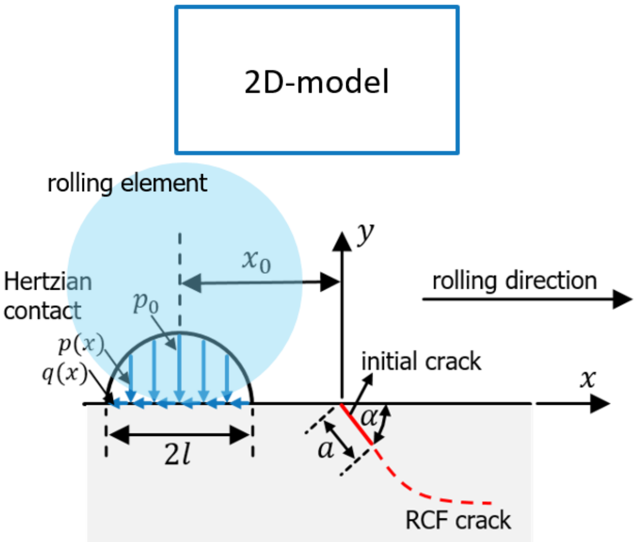

Figure 21: 2D approach for FE simulation

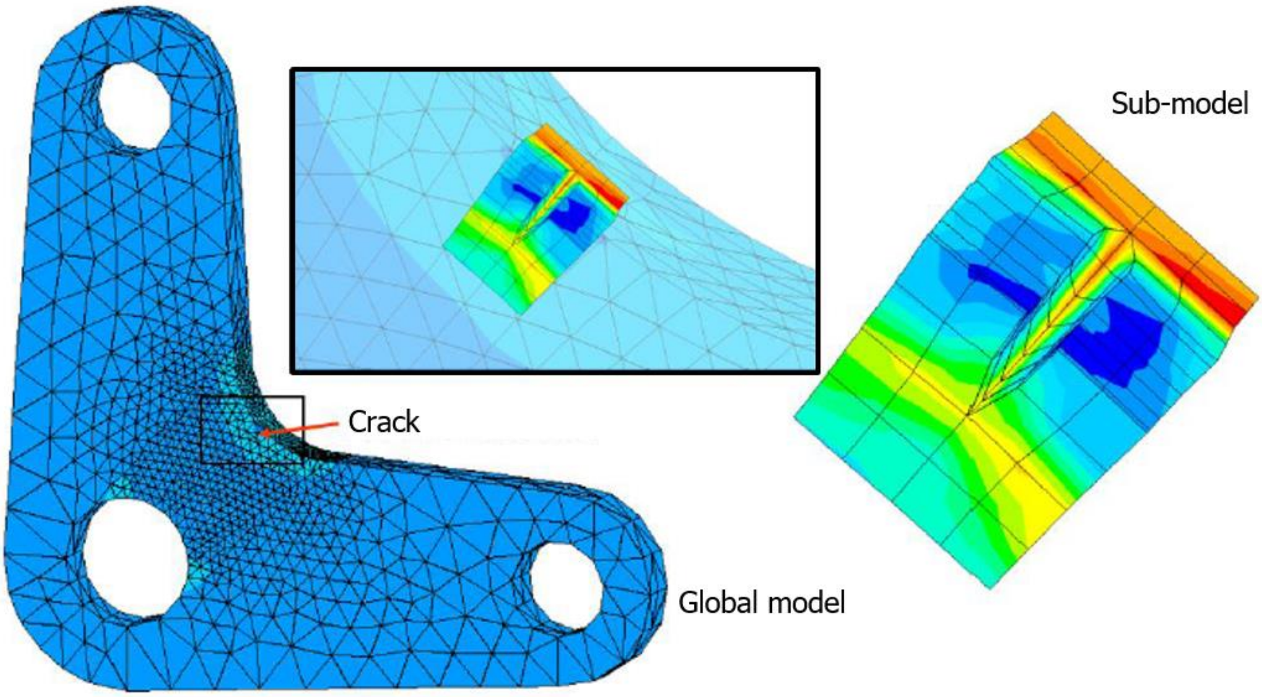

Figure 22: Example of global model and sub-model [9]

As the crack simulations are ongoing, no further information can be provided at this stage of the project. Additional information regarding the simulation and the results will be given within reports D2-4 and D2-5 as applicable.

4. References

References for which the revision status is not provided refer to the last completely signed and therefore approved version.

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D2-1: S. Hilleke et al., "Review of the state-of-the-art design criteria for reliability and flaw tolerance in integrated bearing races and list of relevant design parameters identified", 31 August 2021

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Annex A - Test stands

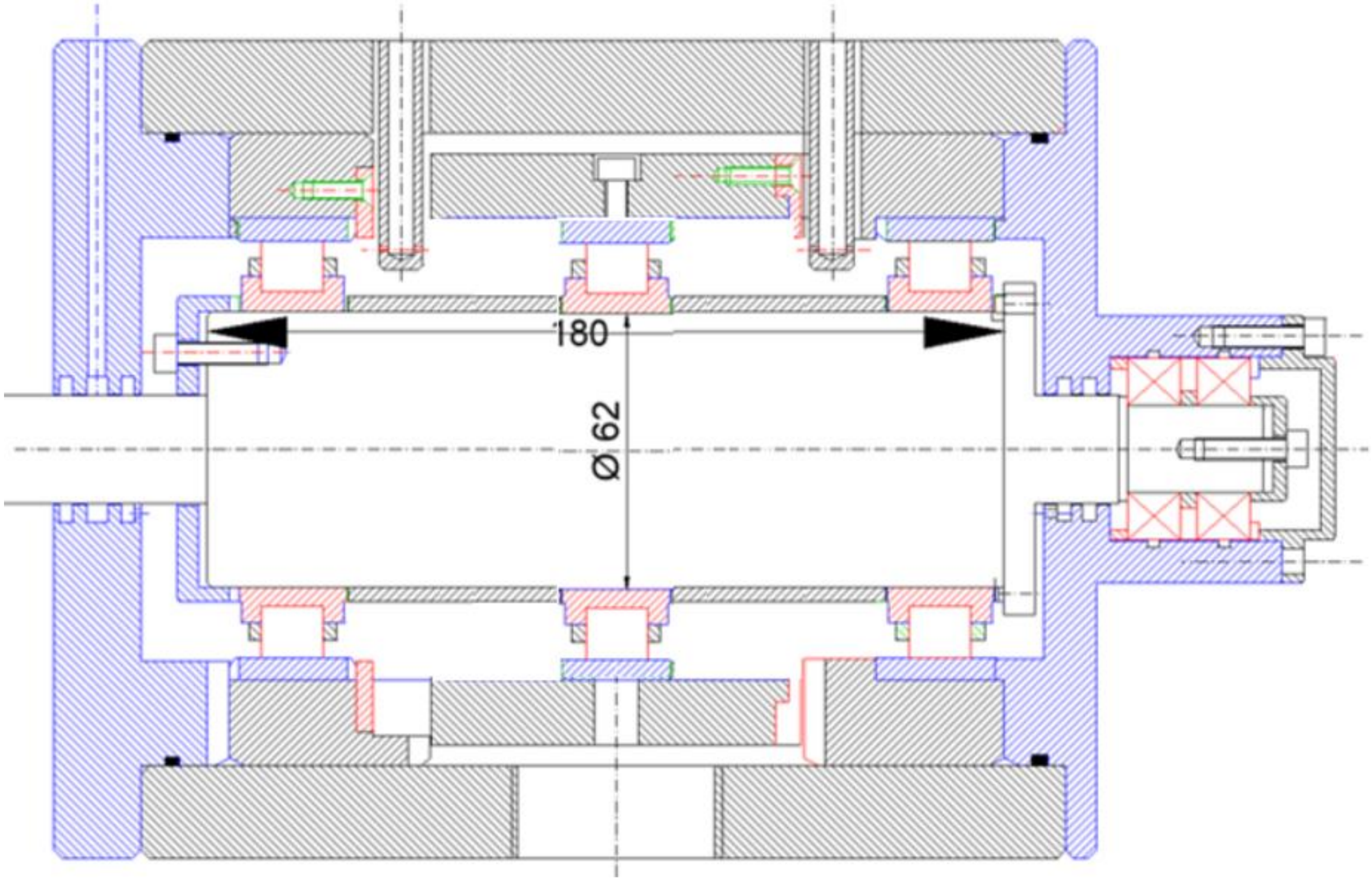
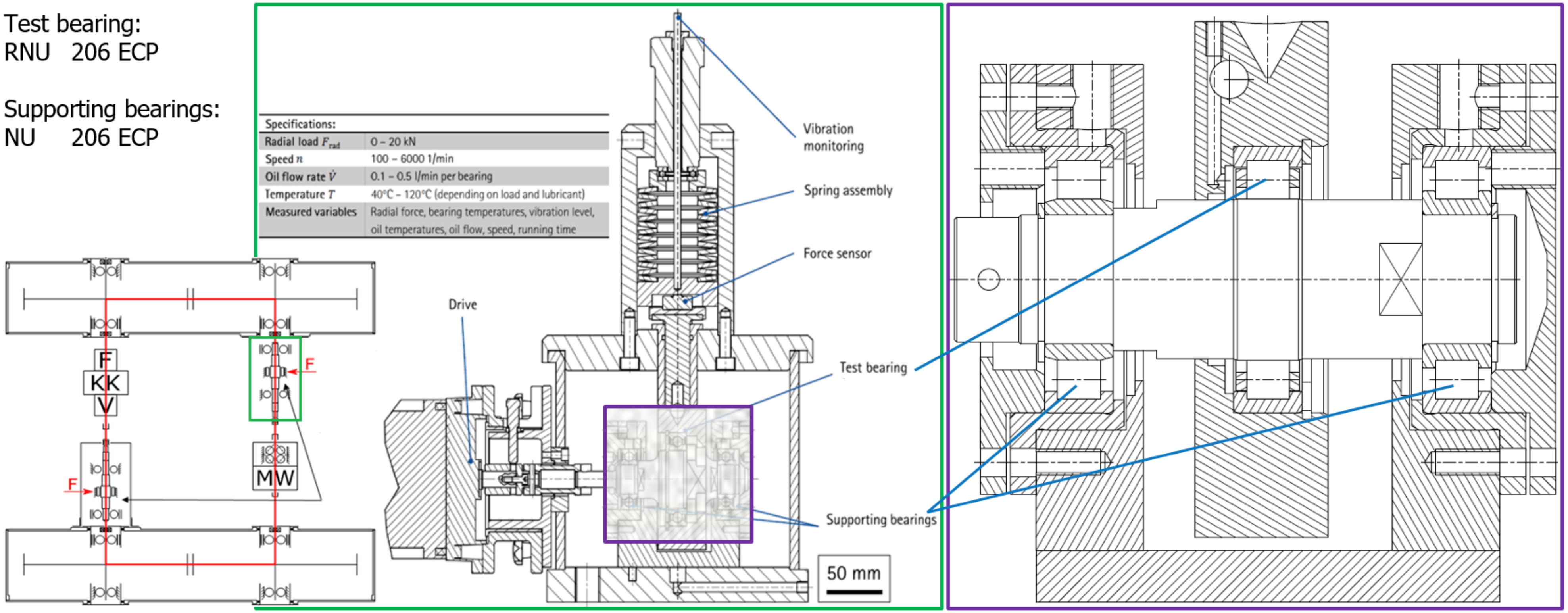


Figure 23: Test head bench #1

Test bearing:
RNU 206 ECP

Supporting bearings:
NU 206 ECP



Specifications:	
Radial load F_{rad}	0 – 20 kN
Speed n	100 – 6000 1/min
Oil flow rate $\dot{V}$	0.1 – 0.5 l/min per bearing
Temperature T	40°C – 120°C (depending on load and lubricant)
Measured variables	Radial force, bearing temperatures, vibration level, oil temperatures, oil flow, speed, running time

Figure 24: Test bench # 2

Annex B - Specimens

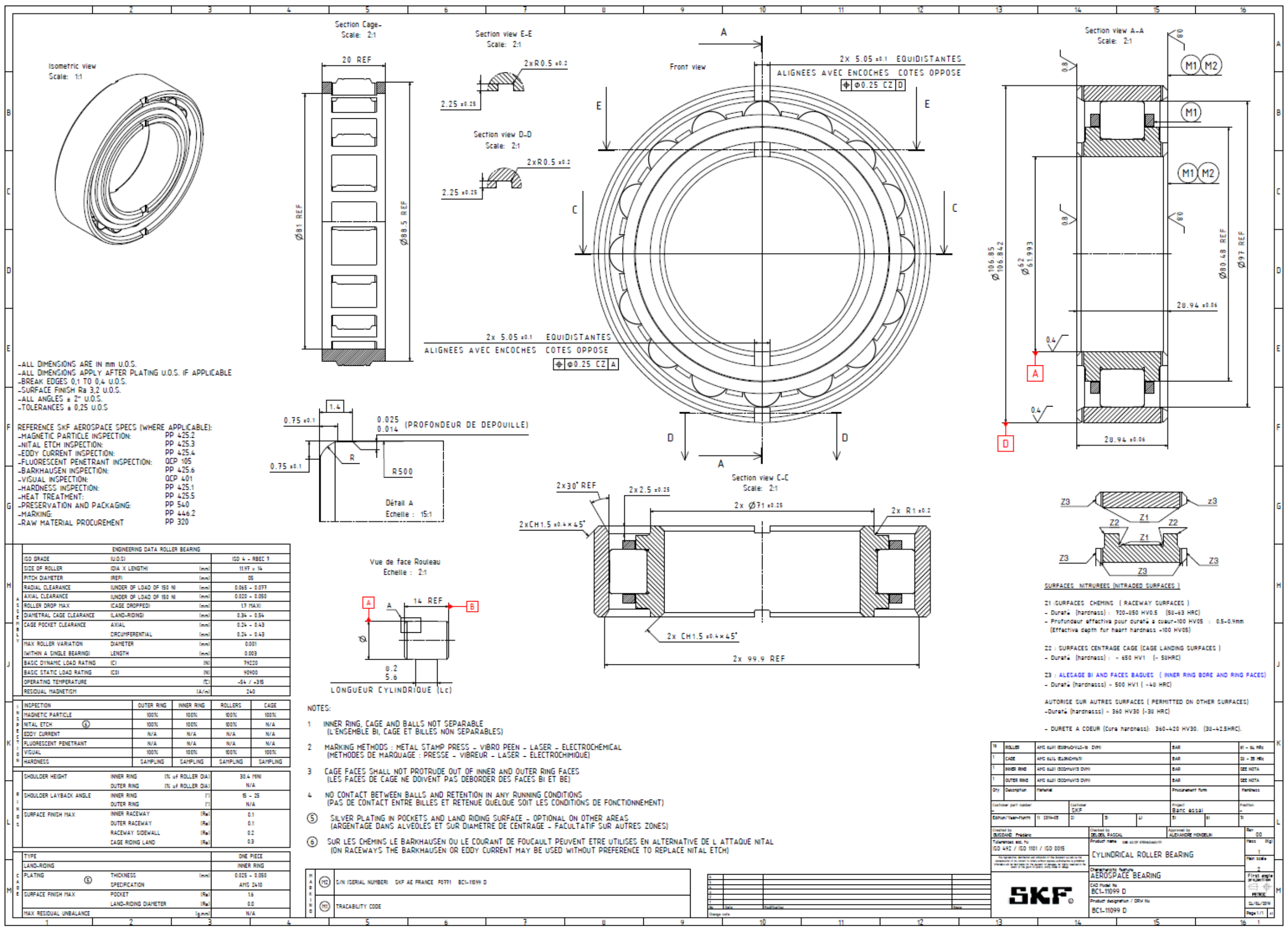


Figure 25: Preliminary specimen geometry for test bench without notch #1

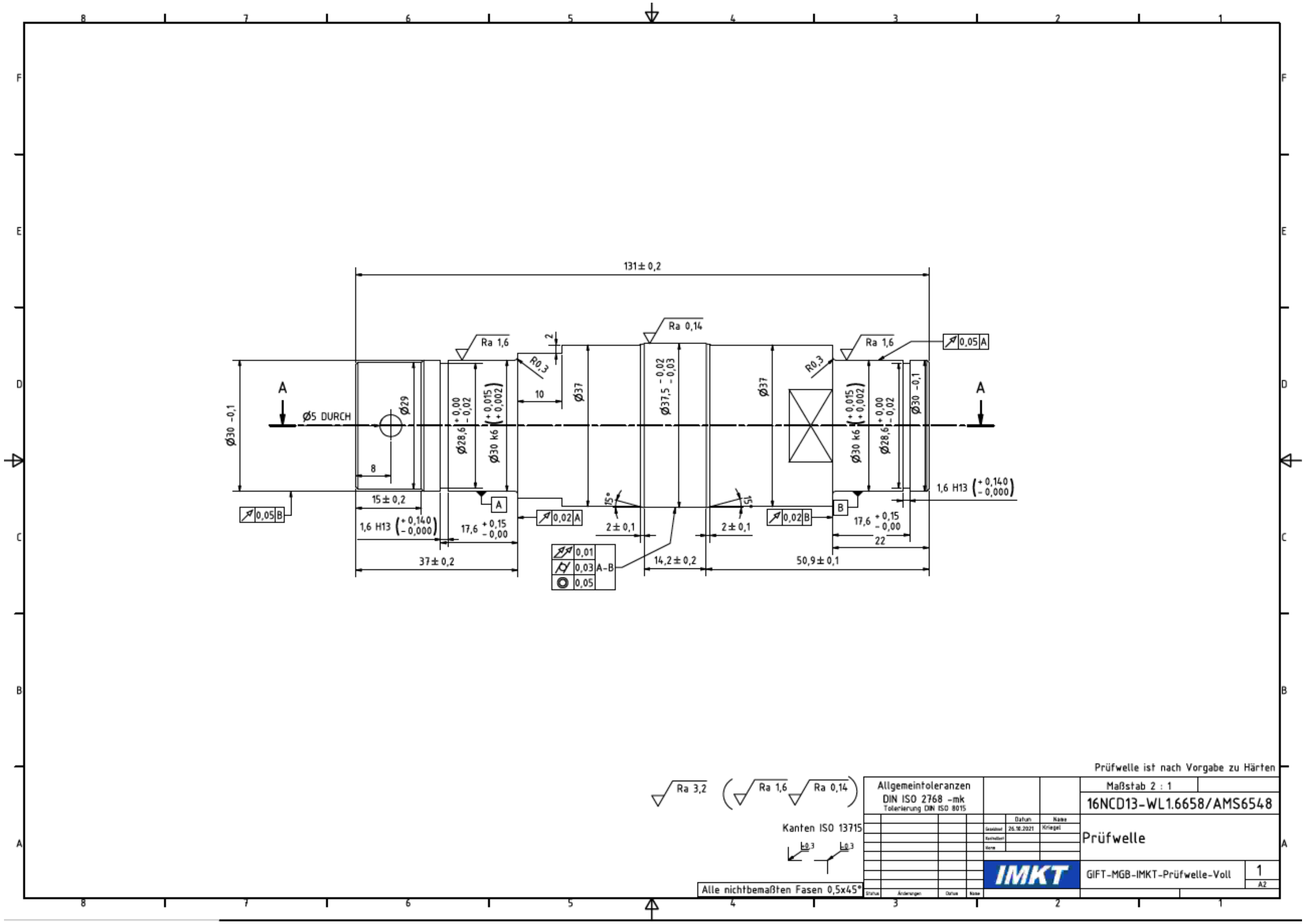


Figure 26: Preliminary specimen geometry for test bench #2 – phase I

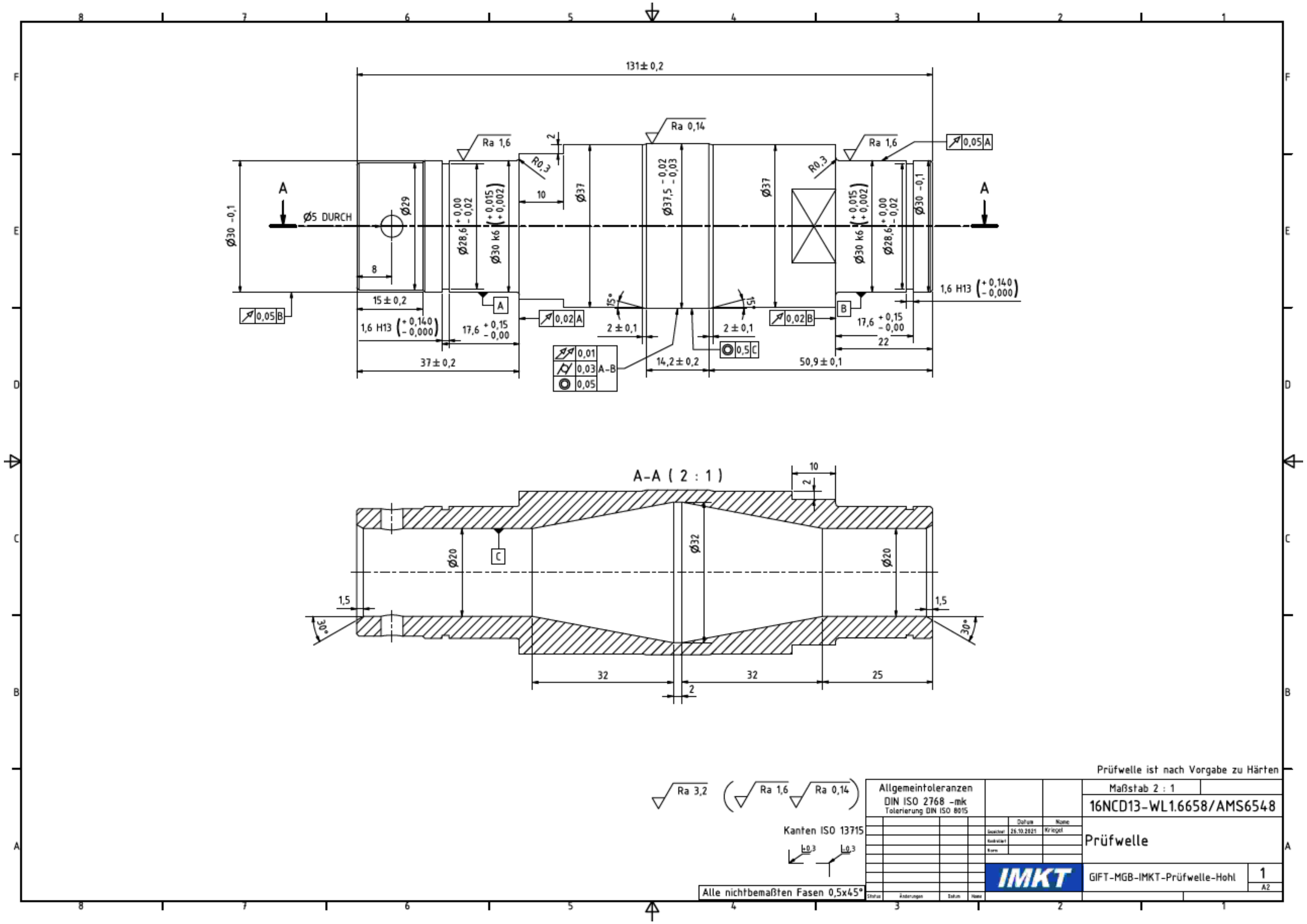


Figure 27: Preliminary specimen geometry for test bench #2 – phase II

Annex C - Indentations

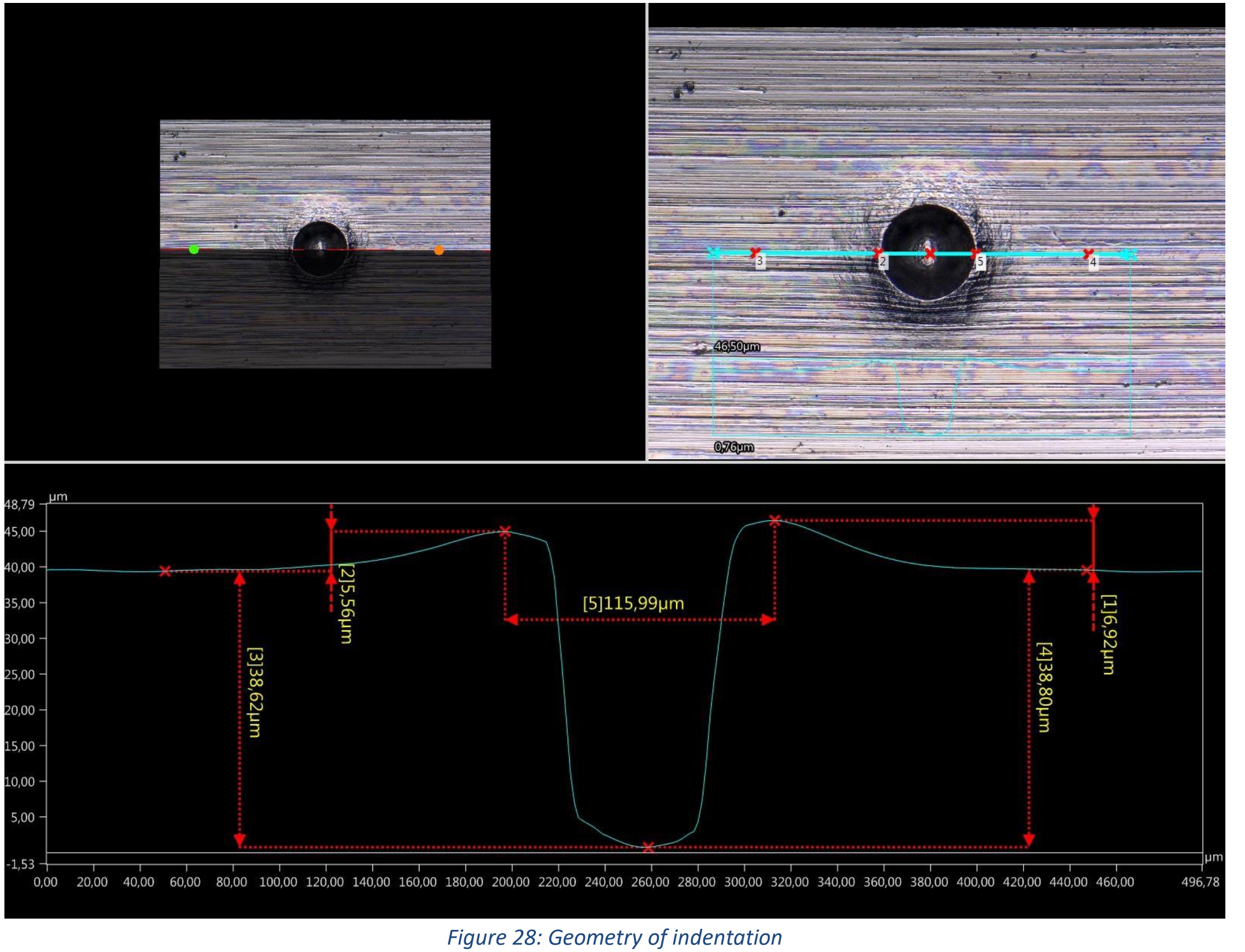


Figure 28: Geometry of indentation

Annex D - Test bearing test #2

Figure 29: Bearing type for test stand #2

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