PROJECT FINAL REPORT

"Publishable"

Grant Agreement number: CS-GA-2014-632472

Project acronym: HIPSGEAR

Project title: Scouting HIgh Performance Steels for GEARs and bearings

Funding Scheme: Industry – 50%; SME – 75%

Period covered: from 01.04.2014 to 31.12.2016

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[2] The home page of the website should contain the generic European flag and the FP7 logo which are available in electronic format at the Europa website (logo of the European flag: http://europa.eu/abc/symbols/emblem/index_en.htm ; logo of the 7th FP: http://ec.europa.eu/research/fp7/index_en.cfm?pg=logos). The area of activity of the project should also be mentioned.

4.1 Final publishable summary report

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INTRODUCTION
Today's engines and their main components such as reduction gear boxes, rely on traditional gears and rolling element bearings of steel. No alternative technology is currently available off the shelf. Based on the experience gained in the earlier Brite Euram projects 'Advanced Surface Engineering Techniques for Future Aerospace Transmissions' (ASETT), this programme proposes the validation of innovative gear and bearing technology under extreme engine conditions utilizing advanced materials and surface engineering techniques, in order to increase engine efficiency.

High applied loads, high speeds and extreme lubrication conditions that gears usually experiments in aeronautical engines lead them to be subjected to severe stress at the tooth root, high contact pressure and contact temperature with a consequent need of a more accurate evaluation of bending, scuffing and pitting capability.

To overcome these problems, the following main RTD activities are a necessity:

1. new, improved and more durable materials and material processing technologies in order to increase
- component life under high load and speed
- wear resistance under contamination and boundary lubrication

2. New and verified stress and life analysis methods to fully consider the improved material capabilities.

MATERIALS SELECTION
Innovative high strength materials, suitable for both gears and bearings were scouted, taking also into account the optimal surface heat treatment. The main focus was on commercial available high strength materials in aerospace quality (VIM VAR).
All selected materials were characterized by means of tests on bearings and gears.

In a first step technical and commercial criterias were defined regarding use as bearing and gear material. The evaluation criterias are as follows:

Technical criterias:
- surface hardness
- core hardness
- hot hardness (core – case)
- maximum case depth
- Ultimate tensile strength of core material
- Yield strength of core material
- fracture toughness of core material

- maximum application temperature
- wear resistance
- thermal conductivity
- possibility of heat treatment
- corrosion resistance

Commercial criterias:
- availability of the material
- machinability of the material
- costs per kilogram
- delivery time
- supply base
- patent situation

In a second step potential high strength materials were selected and all available data regarding technical and commercial criterias were collected using all relevant test data generated within previous projects and using publications and literature data.
The first material selection resulted in the following materials, whereas M50NiL was set as baseline material for bearings and Pyrowear 53 for gears:

- Pyrowear 675 (heat and corrosion resistant carburizing stainless steel)
- CSS-42L (heat and corrosion resistant carburizing stainless steel)
- Ferrium C61 (case-hardened gear steel with ultrahigh strength core)
- Ferrium C64 (case-hardened gear steel with ultrahigh strength core)
- 32CDV13 (deep-nitriding steel)
- 32CDV5 (deep-nitriding steel)
- W460 (ultra high strength steel)

The mechanical properties of the materials are summarized in table 1:

		Mechanical Properties				
variant	material	0,1%YS [MPa]	UTS [MPa]	K_{ic} (core) [MPa√m]	surface hardness [HRC]	core hardness [HRC]
1	M50NiL (Baseline)	1140	1350	60	62 - 64	45
2	Pyrowear 53	950	1150	125	60 - 64	35
3	W460	1800	2200	40	62 - 64	55
4	Pyrowear 675	1050	1250	120	62 - 65	40
5	32CrMoV13	1060	1250	130	62 - 64	40
6	CSS-42L	1350	1700	110	64 - 68	52
7	32CrMoV5	1175	1250	130	62 - 64	40
8	Ferrium C61	1550	1650	140	60 - 62	48 - 50
9	Ferrium C64	1370	1580	90	62 - 64	48 - 50

Table 1: Mechanical properties of high strength materials (surface hardness after typ. heat treatment, all other properties of core material)

An evaluation matrix was created which was filled by regarding bearings and gears requirements on high strength materials. Afterwards both results were combined to define the three most promising materials for gears and bearings.

Because of the significantly different overall ranking of gears and bearings, the final selection of the materials was jointly made. The chosen high strength materials for the screening tests are as follows:

- M50NiL as Baseline
- Pyrowear 675
- CSS-42L
- Ferrium C61

For the identified adequate materials a technology development plan was performed, based on previous bearing and gear test results and field experiences, to explain and underline expected improvements compared to the current state of the art technologies.
There are two different requirements on the properties of the test specimens (gears and bearings):

a) surface hardness in the range of 60 to 64 HRC (700 to 800HV) and a case depth in the range averaging 1 mm at 560 HV (product application: power gear boxes, big modulus, typ. 5).

b) surface hardness of at least 60 HRC (700 HV) and a case depth in the range averaging 1 mm at 650 HV (product application: high loaded bearings).

These are the requirements after all machining operations.

HEAT TREATMENT OPTIMIZATION

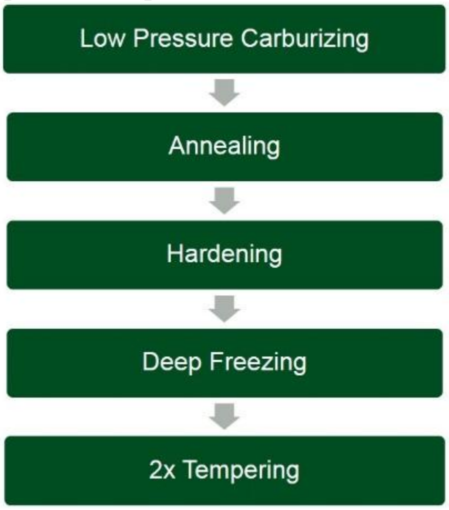
The necessary technology implementation activities such as heat treatment processes, manufacturing and surface finishing technologies, were investigated and evaluated in view of the project time frame. FAG AC performed heat treat studies on bearing and gear test specimens to verify:
- applicability for gears and bearings
- material properties regarding achievable hardness, microstructure and residual stresses.

<u>Pyrowear 675:</u>
Variation of the low pressure carburizing process (optimization of number and duration of boost and diffuse cycles) and optimization of the final heat treatment process (austenitizing temperature, duration and temperature of the tempering cycles) to get the desired case depth and microstructure.

<u>CSS-42L:</u>
Variation of the low pressure carburizing process (optimization of number and duration of boost and diffuse cycles) and optimization of the final heat treatment process (austenitizing temperature, duration and temperature of the tempering cycles) to get the desired case depth and microstructure. In order to avoid the hardness drop in a depth of 3 to 4 mm, it is planned to vary the content of carbon and nitrogen in the carbonitridng process to investigate the influence on retained austenite and hardness drop.

<u>Ferrium C61:</u> Variation of the low pressure carburizing process and optimization of the final heat treatment process. Additionally optimization of a nitriding process (variation of nitrogen content, temperature and duration) to get the desired nitriding depth and microstructure.

As a starting point the following process steps were chosen for P675 and CSS-42L:



In view of the achieved surface hardness, case depth, microstructure, residual stress and retained austenite, the process parameters were adapted as described above.

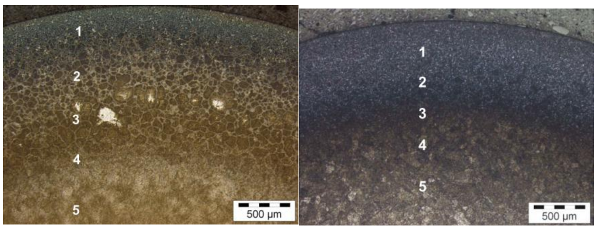
<u>Pyrowear 675</u>

Pyrowear 675 is a case hardening steel which shows, depending on the level of carburizing, a certain corrosion resistance. For this, the content of Chromium is approximately 13% which makes the carburizing difficult due to the formation of a passive layer. Therefore the carburizing method applied for Pyrowear 675 was low pressure carburizing. It is known that the cracking hydro carbons used in low pressure carburizing are able to remove passive layers and enable a homogeneous carburizing even of high Chromium steels. The low pressure carburizing process is characterized by alternating cyclic application of boost (carburizing) and diffuse (soaking) cycles. The typical process gas in a boost cycles is a mixture of acetylene and hydrogen. The carbon profile resulting from a low pressure carburizing process depends on the number and duration time of the boost and diffuse cycles. By a variation of these cycles a variation of the carbon profile and hardness profile is possible. For the ball on rod test two carburizing variants of Pyrowear 675 were manufactured:

- variant 1 with a high content of carbon, high hardness and high amount of carbides
- variant 2 with lower content of carbon, lower hardness lower amount of carbides.

The subsequent austenitizing was performed for both variants, also deep freezing and tempering two times was the same for both variants.

Figure 1 and Figure 2 show the microstructure of the two P675 variants in an overview and in different depths, Figure 3 the according hardness profiles and Figure 4 the residual stress profiles.



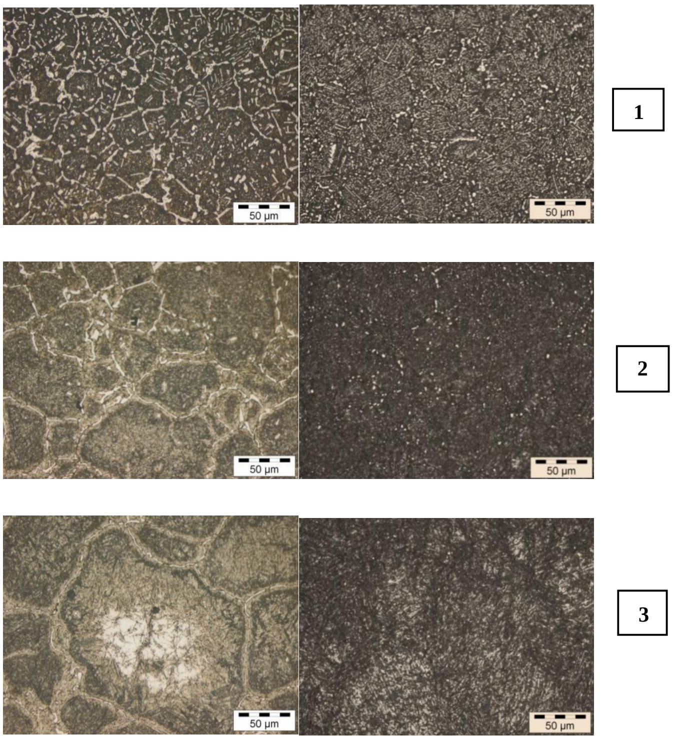


Figure 1: Microstructure P675, variant 1   Figure 2: Microstructure P675, variant 2

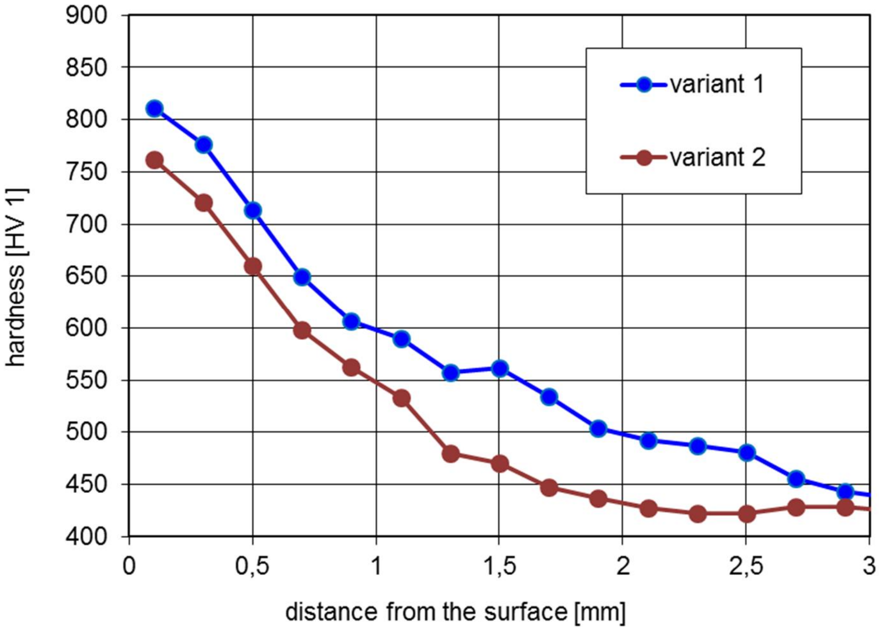


Figure 3: Hardness profiles of Pyrowear 675 rods, finished machined cond.

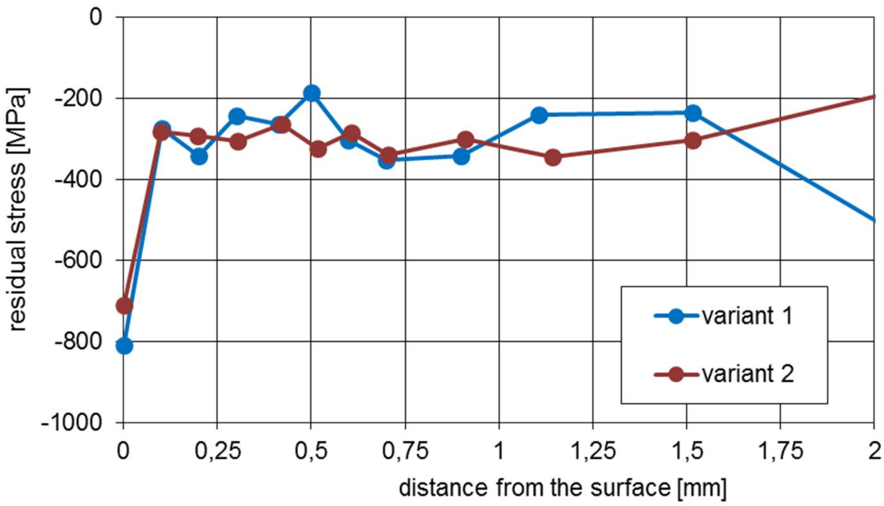


Figure 4: Residual stress profiles of Pyrowear 675 rods, finished mach. cond.

Additionally to variant 1 and 2 two carburizing variants, 3 and 4 were performed.
In case of variant 3 a hardness close to the finished surface of approximately 700 HV was intended, variant 4 should be similar to variant 2 with a different combination of the pulse-pause ratio during carburizing. Figure 5 shows the hardness profiles of all Pyrowear 675 variants.

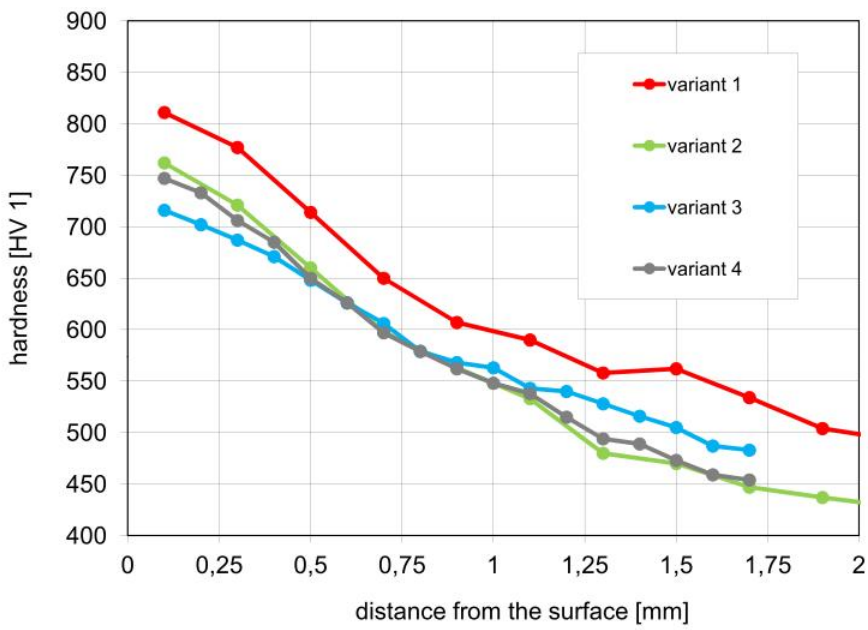


Figure 5: Hardness profiles of all Pyrowear 675 variants

<u>CSS42-L</u>

CSS42-L is, similar to Pyrowear 675, a case hardening steel which shows, depending on the level of carburizing, a certain corrosion resistance. The content of Mo and Co is considerably higher than in Pyrowear 675, therefore the hardness in a similar carburized case is expected to be higher than in Pyrowear 675.

In a first step the heat treating cycle applied for Pyrowear 675 variant 1 was applied on the rods of CSS42-L. Figure 6 shows the microstructure close to the surface of a finished machined rod, Figure 7 the according hardness profile.

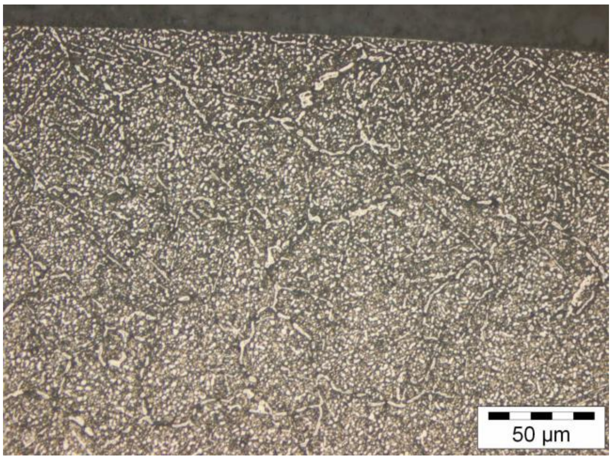


Figure 6: Microstructure at the surface of a CSS42-L rod

The hardness profile shows a significant drop in the transition zone between carburized case and core material. An analysis of the retained austenite is difficult in case of this material due to the high content of carbides. These carbides cause peaks in the diffraction pattern which superimpose the austenite and martensite peaks and make an evaluation very difficult. An estimation of the retained austenite content resulted values of more than 50% in a depth of 1 to 2 mm. Micrographs in this region show a bright appearance which is also an indication of high retained austenite.

Retained austenite is a metastable microstructure which can transform into martensite when exerted a higher temperature or load. This transformation causes dimensional changes which are not desirable in many applications.

In order to reduce the drop in hardness, a higher tempered variation was produced, but there was no marked improvement in the hardness drop.

A carburizing according to variant 2 was also applied, but there was no marked improvement regarding the drop in hardness.

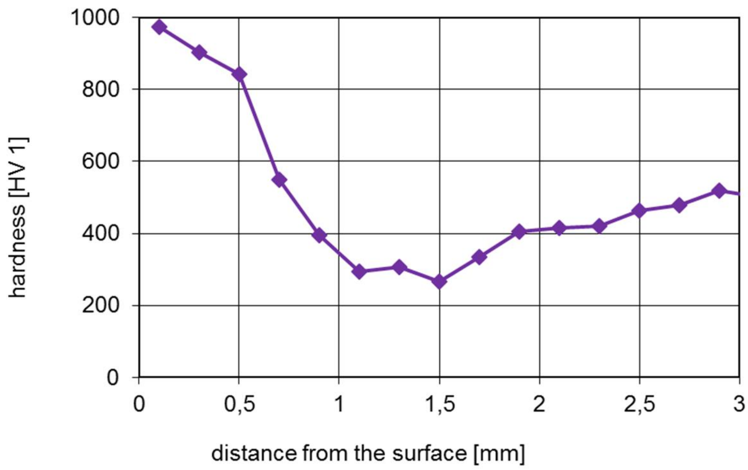


Figure 7: Hardness profile of a CSS42-L rod,

finished machined condition (carburized acc. variant 1 P675)

In order to get a hardness profile without a drop in hardness at the transition zone between the carburized case and the core material a nitriding of CSS-42L without a prior carburizing was performed. A plasma process was applied in order to remove a passive layer on the surface (by an initial sputtering) which might inhibit the transition of nitrogen into the material. The nitriding temperature was adjusted in order to get a high diffusion rate and a surface hardness in a range of app. 900 to 1000 HV. Figure 8 shows the hardness profile after nitriding, Figure 9 the microstructure. The surface hardness is in the range between 900 and 1000 HV (extrapolated), but the nitriding depth is below 0,1mm in the as nitrided condition. This is far away from what we need for gear and bearing applications. Therefore no tests were performed with rods in this condition. Figure 9 shows a sharp transition between the diffusion zone and the base material which is typical for high chromium steels.

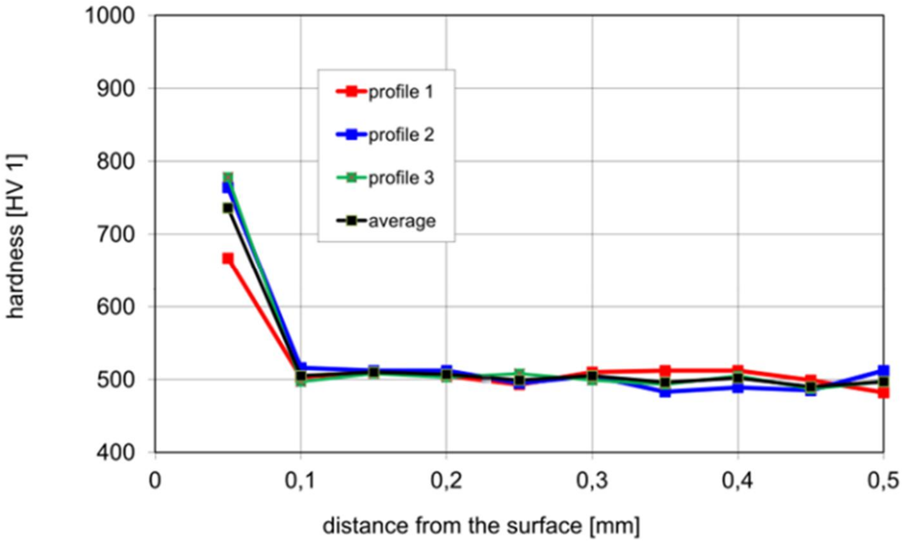


Figure 8: Hardness profiles of CSS-42L nitrided

as nitrided condition

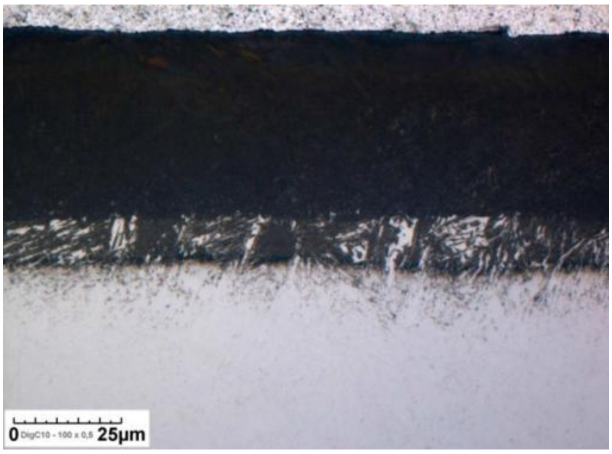


Figure 9: Microstructure of CSS-42L nitrided
diffusion zone (no white layer)

<u>Ferrium C61</u>

Ferrium C61 is a high alloyed carburizing steel which offers a very high core strength. Figure 10 shows the microstructure of the carburized zone, Figure 11 a hardness profile of the carburized case in the as carburized condition.

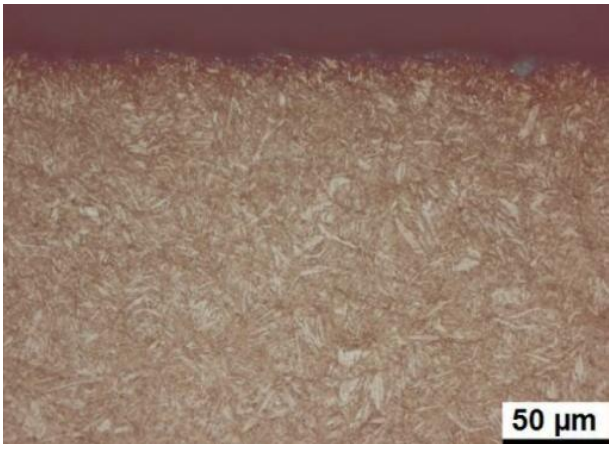


Figure 10: microstructure of Ferrium C61, carburized case
as hardened condition

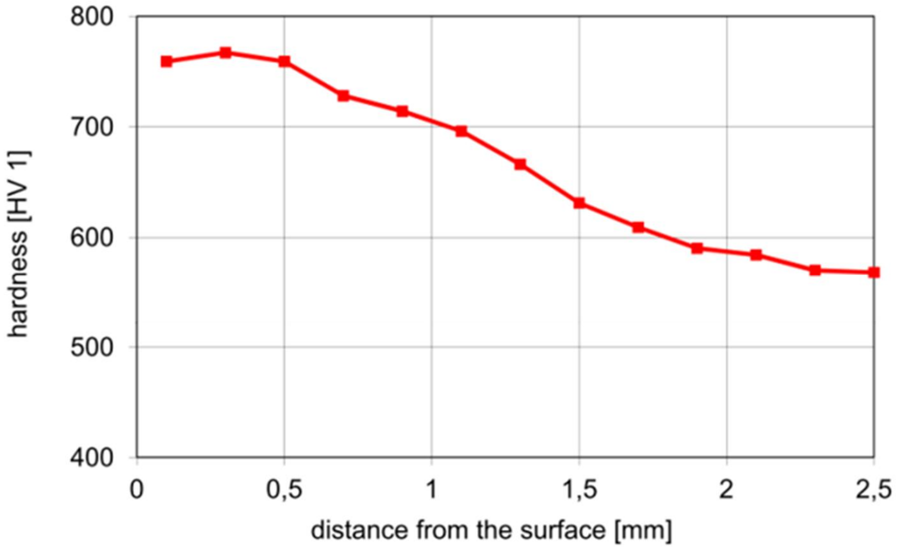


Figure 11: Hardness profile of Ferrium C61
as hardened condition

In case of Ferrium C61 a nitriding additional to the carburizing was tested. This results in a marked increase in hardness close to the surface which might be beneficial for rolling contact fatigue. A nitriding process was performed after carburizing and hardening and grinding.
After the nitriding the surface of the specimens was polished (no grinding). Figure 12 shows the microstructure of the nitride zone, Figure 13 the according hardness profile.

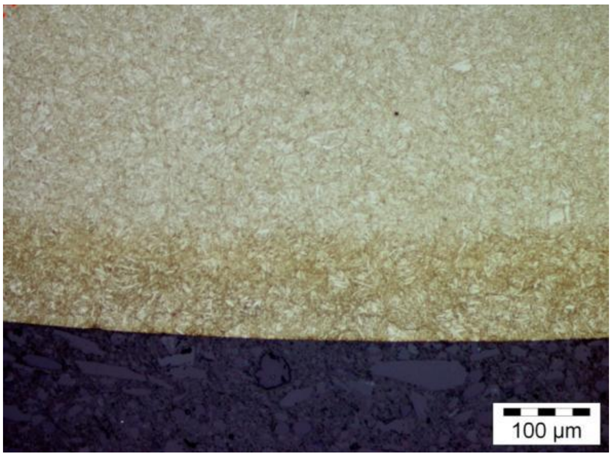


Figure 12: Microstructure of Ferrium C61
carburized and nitrided

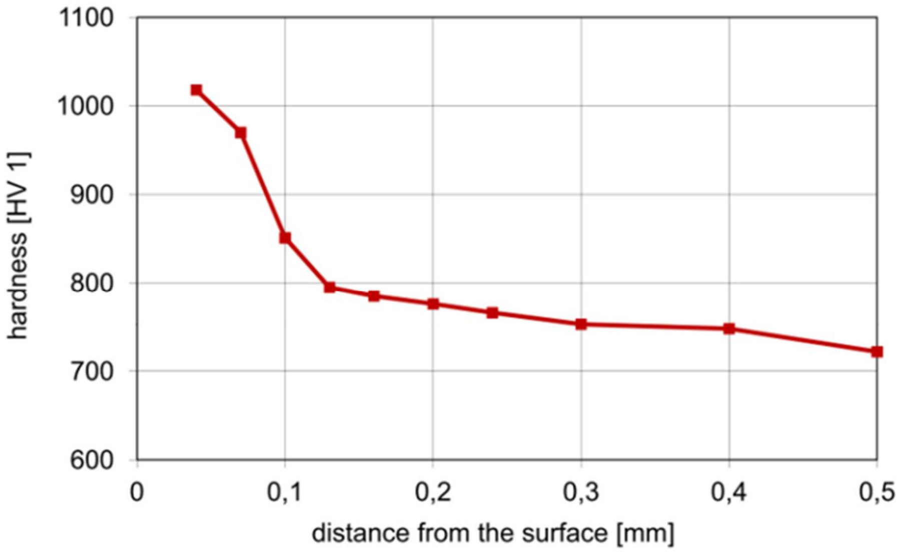


Figure 13: Hardness profile of Ferrium C61
carburized and nitrided
as nitrided condition (only polished)

Base material characterization

Tensile tests were performed to determine the typical tensile properties of the different core materials:

- Ultimate (tensile) strength
- Yield (tensile) strength
- Elongation
- Reduction in area

The test specimens were heat treated according to the developed heat treatment process, see Fig. 14.

Figure 14: Heat treatment process of tensile specimens

The carburization was replaced by tempering at the same temperature and duration. All other heat treatment steps were unchanged.
The material Ferrium C61 was delivered by Topic Manager.
Tensile specimens according to DIN 50125 – B6x30 were machined from M50NiL, Pyrowear 675, CSS-42L and Ferrium C61, Figure 15 shows the dimensions of the test specimens.

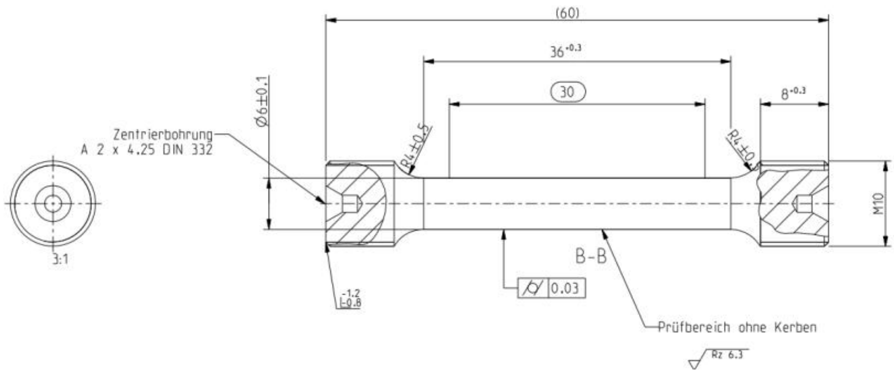


Figure 15: Dimensions of the tensile test specimen

The tests were performed on a Zwick 100 testing machine according to EN ISO 6892-1 at ambient temperature, the loading rate was 10MPa/s.
The experimental results are reported in table 2, every value in table 2 is the average of values from three tensile tests.

material	E [GPa]	$R_{P0,01}$ [MPa]	$R_{P0,1}$ [MPa]	$R_{P0,2}$ [MPa]	R_m [MPa]	A [%]	Z [%]
M50NiL	100%	100%	100%	100%	100%	100%	100%
Pyrowear 675	102%	89%	90%	90%	91%	108%	99%
CSS-42L	88%	90%	102%	101%	131%	110%	78%
Ferrium C61	92%	145%	136%	137%	147%	71%	51%

Table 2: Experimental results of the tensile tests

Notable is the comparatively low modulus of elasticity of CSS-42L and Ferrium C61. In both alloys the content of Co is rather high, CSS-42L app. 12% and Ferrium C61 approximately 18%. It is known from literature that some alloys containing a high content of Co, e.g. Marage 300, show a similar behaviour.

The ultimate strength of CSS-42L and Ferrium C61 is considerably high compared to M50NiL and Pyrowear 675. The yield limit ($R_{P0,01}$) of CSS-42L is similar to M50NiL and Pyrowear 675 whereas the yield limit of Ferrium C61 is the highest of all tested materials.

The stress-strain curves for all tested materials are shown in Figure 16.

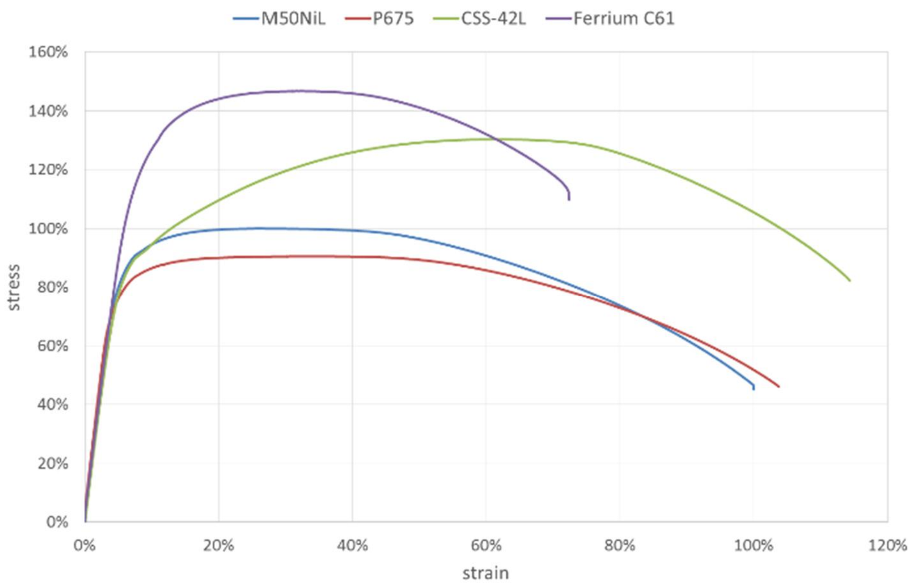


Figure 16: Engineering stress-strain curves for all tested materials (values are normalized to M50NiL)

RCF SCREENING TESTS

Based on past experience the results of trials test were not sufficient to enable the choice of the combinations of materials / heat treatment to explore with test on components.

For this reason a dedicated WP has been introduced in order to perform screening test on Ball-on-Rod test rig and have a more complete indication of the selected material surface resistance. Screening test will represent an early indicator of the project success and will eventually minimize the risk to choose the wrong materials for the planned bearing and gear tests.

A preliminary test with M50NiL will be carried out to assess the capability of the selected new materials in comparison to a well-based material for aerospace applications (bearings).

All screening test will be performed on a Ball-on Rod Test Rig (see figure 17). The test specimen is the test rod of various materials. The balls are of standard M50 material. The test rod is driven by a direct drive with a speed of approx. 3.000 rpm.

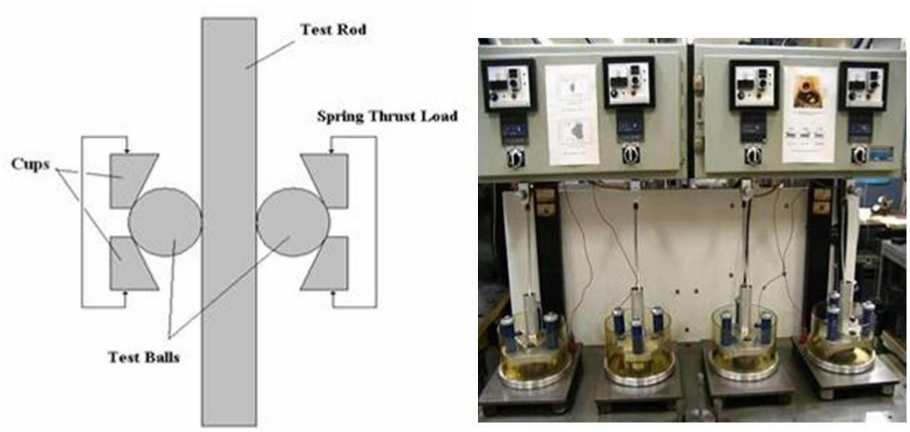


Figure 17: Ball-on Rod Test Rig, caps: tapered rings

All screening tests will be performed at a load high enough to generate material failures within short time. A Wöhler diagram was used to estimate the endurance life of the M50NiL – Baseline material (see figure 18). It was decided to use a Hertzian pressure resulting in approx. 1,0 x 10^7 load cycles. The suspension time was set to 3,0 x 10^8 load cycles. Therefore it is guaranteed that the new high strength materials (P675, CSS-42L and Ferrium C61) can show their potential regarding rolling contact fatigue in comparison to the Baseline material and that the screening tests can be finished in a sufficient time. The rotational speed of the test rig is fixed at a speed of 3.000 rpm, therefore the load is the only possibility to influence the testing time.

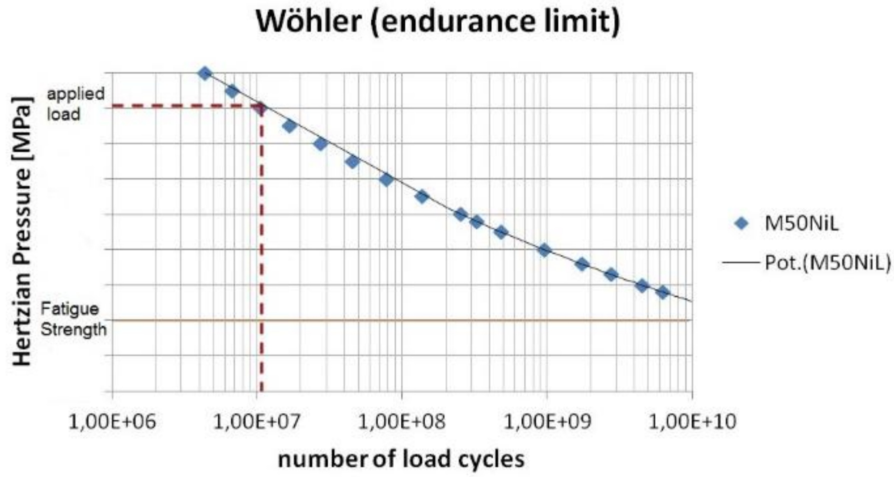


Figure 18: Wöhler diagram – M50NiL (Baseline)

Shell Morlina 46 was used for lubrication. This is a well-known oil which is usually used for endurance testing. The rod temperature during testing is between 50°C to 70°C. This results in lambda value of approx. 0,23.

The suspension criteria was defined by vibration (rod failure) or the suspension time is reached. Only rod failures were taken in consideration. In the case of a ball and / or tapered ring failure, the test has to be repeated. It was decided to create 12 rod failures for the Baseline to have a statistical secured result. For the other high strength materials, it was decided to have at least 6 rod failures depending on the running time.

In Table 3 shows a summary of the test conditions on the Ball-on-Rod test rig:

Number of test specimens	6 resp. 12 (for Baseline)
Speed of rod	3.000 rpm = const.
Load cycles per hour	424.260 cycles / hour
Suspension time	3 x 10^8 load cycles
Lubrication	Shell Morlina 46
Temperature	50°C – 70°C
lambda	ca. 0,23
Suspension criteria	vibration (rod failure) or suspension time

Table 3: Test parameters of Ball-on-Rod Testing

For the M50NiL (Baseline) rod specimens a standard heat treatment for Aerospace main shaft bearing was applied. The material investigations were performed on the rods in the finished condition.
A surface hardness of 760 HV1 was achieved. The case depth is about 1,20 mm at 560 HV1 (53 HRC) (figure 19). Therefore the requirements of gears and bearings (chapter 1) are fulfilled.

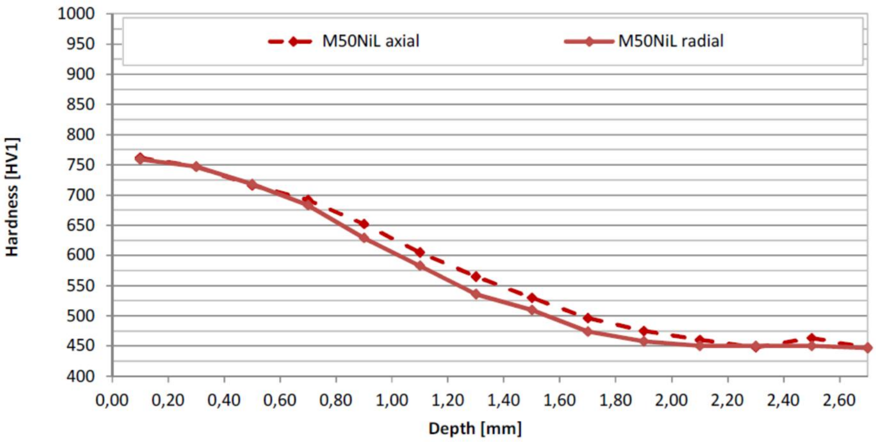


Figure 19: Hardness profile M50NiL – finished condition

The texture shows fine needle shaped martensite at the surface (figure 20) and core (figure 22). The grain size is about RZ5 occasionally even RZ3.

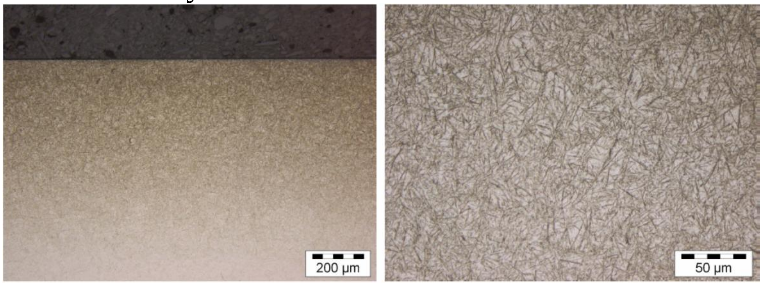


Figure 20: M50NiL Surface – Martensite (Magnification: 100X resp. 500X)

The carbide distribution (figure 21) corresponds to Level 1. No carbide network is visible.

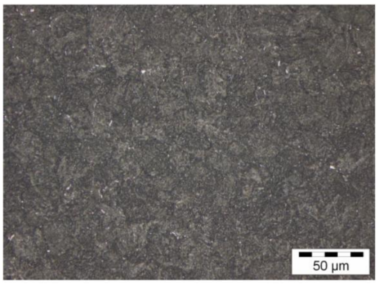


Figure 21: M50NiL Carbide distribution (100X)
Figure 22: M50NiL Core – Martensite (1000X)

The residual stress profile is typical for M50NiL. Showing a maximum compressive stress of about 250 MPa up to a depth of 0,7 mm and in higher depth a continuous increasing to a residual stress of -100 MPa in a depth of 2 mm. The full width at half maximum starts at almost 6° and decreases to 2,8° in a depth of 2 mm (figure 23). This correlates ~~very~~ well with hardness profile of figure 19.

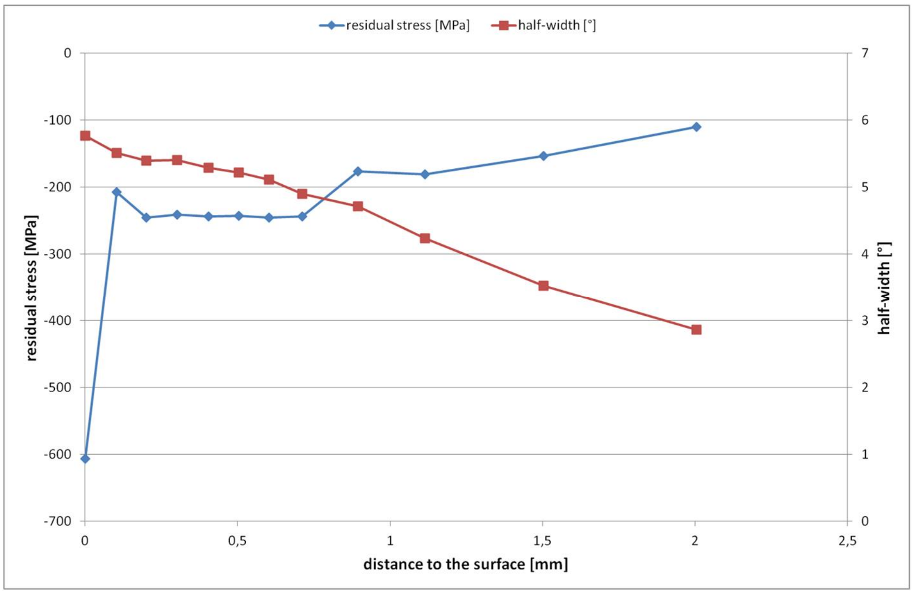


Figure 23: Residual Stress and full width at half maximum - M50NiL rod

The running time of the M50NiL rods was evaluated in a Weibull diagram.

Summary Ball-on Rod Testing

The material and heat treatment combinations can be clustered in two sections (table 4).

Section 1 (medium performance): Pyrowear 675 (2nd heat treatment) & M50NiL (Baseline)

Section 2 (high performance): Pyrowear 675 (1st and 3rd heat treatment), Ferrium C61 (carburized)

	M50NiL	**C61 (carb.)**	**P675 (1st HT)**	**P675 (2nd HT)**	**P675 (3rd HT)**	**CSS-42L**
Relative B10 life compared to M50NiL	**1**	**7,3**	**8,0**	**0,74**	**10,2**	**20,6**

Table 4: Overview of Ball-on Rod Testing results

Besides the rolling contact fatigue behaviour the achievable hardness profile, residual stress profile, case hardness depth and microstructure has to be considered to decide which material should be selected for the bearing and gear testing.
The RCF performance of CSS-42L is faraway the best of all high strength materials, but the hardness profile and microstructure do not fulfil the requirements of gears and bearings. Therefore this material can not be selected for the further tests.
The RCF performance of P675 (1st HT and 3rd HT) is almost comparable. But the microstructure of the 3rd HT version is better (slighter carbide network) than HT version one.
Therefore it was decided to select P675 (3rd heat treatment) and Ferrium C61 (carburized) for the bearing and gear tests.
The baseline for the bearing test will be M50NiL-DH.
The single bending tooth fatigue tests of gears will be performed on Ferrium C61 (carburized) and M50NiL-DH.

BEARING TESTING RESULTS

All bearing tests were performed with modified angular contact ball bearings comparable to bearing type 7205. Only the inner rings were manufactured from the new high strength material and therefore considered as test specimen. Potential outer ring and ball failures were not considered in the Weibull evaluation.
The principle of the test rig L17 is shown on Figure 24.

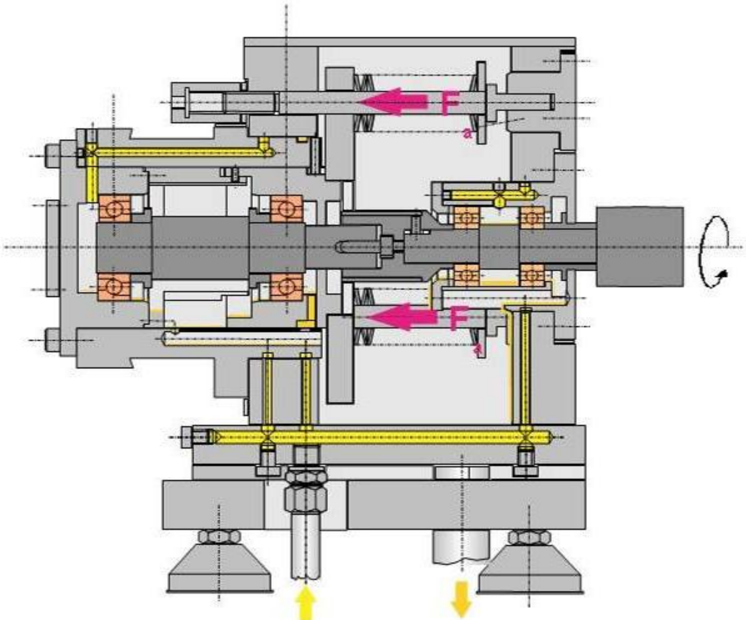


Figure 24: FAG test rig – L17

The test rig is equipped by a recirculating oil lubrication system for each test bearing, to guarantee equal lubrication condition. A vibration sensor is installed at the housing to shut down the test rig when a failure of a bearing component occurs. The determination what component failed can only be analysed by dismounting the test bearings and performing a visual inspection.

Due to experience in other projects it was decided to run the endurance tests under mixed lubrication (low lambda) conditions, so that you'll get the first spall within reasonable time. The contamination tests run with pre-damaged inner rings caused by a HRC indenter. For the spall propagation tests the spalled bearings of the contamination tests are used under a reduced pressure.

The spall propagation was monitored every 2 to 4 hours (depending on the propagation speed) until 20% of the inner ring circumference was spalled (see Table 5).

Test series	Endurance	Contamination	Spall Propagation
No. of bearings	12	12	12
Speed	12.000 rpm		
Lubrication	EMOL-O-GRIND (low lambda)	Mobil Jet II (full lambda)	
Contamination	no	8 x HRC	spall
Test time	up to 2650 hours	to spall	to bearing failure / 20% of the circumference

Table 5: Test Matrix for L17 Tests

Endurance Testing

In the following table 6 the test results of Endurance testing under mixed lubrication are shown:

Material	**Bearings tested**	**IR failures**	**RelativeB_{10} life**
M50NiL-DH	12	6	100%
P675	8	2	333%
Ferrium C61	10	2	184%

Table 6: L17 Endurance Testing Results

Pyrowear 675 showed a great potential regarding rolling contact fatigue under mixed lubrication condition. The B_{10} life time is more than three times higher than the Baseline M50NiL-DH. The comparable high Weibull slope β causes that almost all bearings reached the suspension time. A continuation of the tests will provide better statistical based results. Also Ferrium C61 could show his great RCF potential, resulting in a 1,84 times higher B_{10} life time as the Baseline. One infant mortality of an inner ring was caused by a surface initiated defect and therefore not considered for the evaluation.

Contamination Testing

The bearing test campaign was performed with 12 bearings. The maximum test time was fixed until an inner ring spall occurs (apart high running time tests which were suspended).

The pre-damaging of the inner rings was performed by a modified Rockwell indenter. In total 8 HRC indents with different angles (19,2° to 41,6°) distributed over the whole running track circumference were inserted in the inner ring (see figure 25). The indent size was fixed to a diameter of 160 µm.

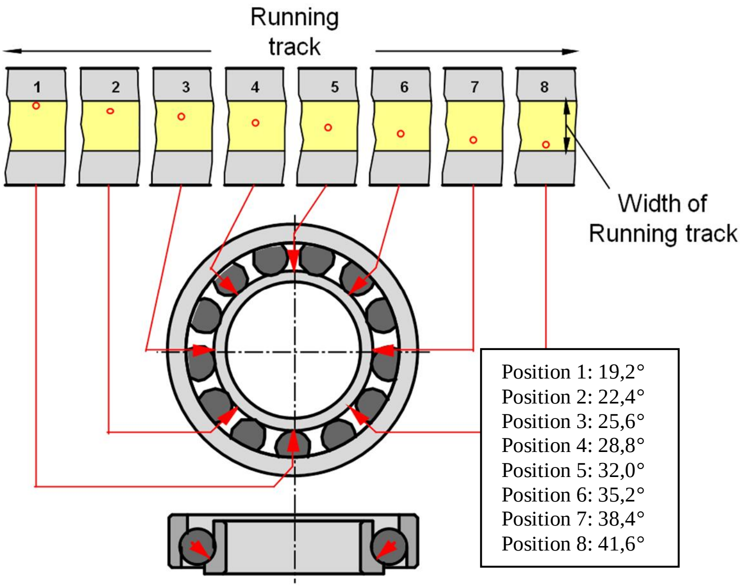


Figure 25: Indentation pattern on inner ring raceway

In the following table 7 the test results of contamination tests are shown:

Material	Bearings tested	IR failures	RelativeB_{10} life
M50NiL-DH	12	11	100%
P675	12	12	11%
Ferrium C61	12	11	2,8%

Table 7: Contamination Testing Results

All failed parts showed a typical inner ring pitting at position 1 (19,2°) to position 4 (28,8°), as it was expected. All other components (balls, outer ring and cage) showed no failures. M50NiL-DH showed a nine times higher B10 life time under pre-damaged condition than P675 and even a 36 times higher life compared to Ferrium C61. Therefore the potential new high strength materials could not confirm their superior performance under contaminated condition. So Duplex Hardening (DH) seems to be a great benefit compared to only pure carburized steels. Both high strength materials can be duplex hardened in principle. So that might be a possible way forward to improve the performance of both steels under contaminated conditions.

Spall Propagation Testing

The failed bearings of the contamination test were used to show the spall propagation behaviour. The initial spall size after the Contamination Test was documented and determined by microscope (figure 26).

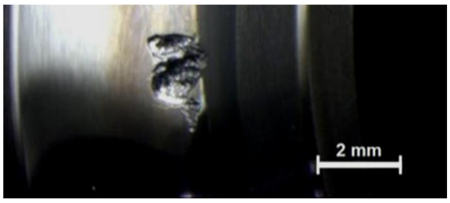


Figure 26: Example of Initial spall size after contamination test

The spall propagation was documented after several hours depending on the propagation speed of the inner ring. The shut down of the test rig was regulated by the vibration signal. The threshold was set to a 10% vibration increase based on vibration level starting the test. The goal was to generate at least 3 to 4 data point for each test bearing.

Each spall propagation test was continued until 20% of the raceway circumference was spalled. In figure 27 is a direct comparison of the spall propagation performance between M50NiL-DH (Baseline), Pyrowear 675 and Ferrium C61 shown. For all materials, the initial spall of the contamination tests is used. For the material P675 only 10 bearings can be used, because the initial spall size is too big and therefore not comparable to the other materials. M50NiL-DH shows the overall best spall propagation performance. The minimum time is almost comparable to the maximum time of the two high strength materials. The maximum running time is 2,3 times longer. The performance of Ferrium C61 is slightly better than Pyrowear 675. The maximum running time is comparable, but the scatter is lower compared to P675. Noticeable is the fact that all initial spalls of Ferrium C61 (independent of initial spall size) show a spall propagation, whereas M50NiL-DH and P675 show no propagation if the initial spall size is under a certain threshold (ca. 0,5 mm x 0,5 mm).

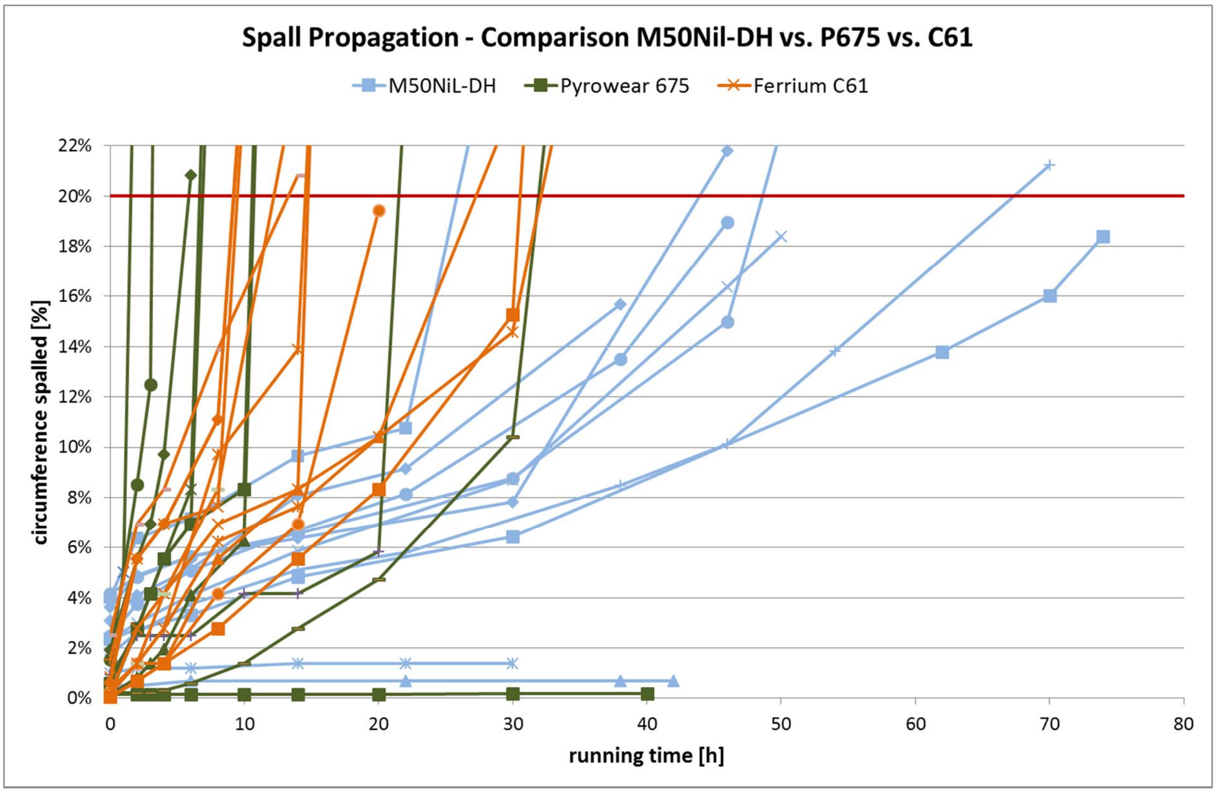


Figure 27: Spall Propagation behaviour – M50NiL-DH vs. P675 vs. C61

To clarify if the better performance of M50NiL-DH is material and/or heat treatment related, it is reasonable to investigate the performance of standard M50NiL. Both high strength materials can be Duplex Hardened and therefore the contamination and spall propagation might be further improved.

SUMMARY

Potential new high strength materials for gears and bearings were scouted and evaluated by an evaluation matrix considering the requirements of gears and bearings. For the most promising materials (Pyrowear 675, CSS-42L and Ferrium C61) the heat treatment was developed and optimized to fulfil the requirements of gears and bearings. In a second step the rolling contact fatigue of each material – heat treatment combination was evaluated on the Ball-on-Rod test rig. P675 carburized and Ferrium C61 carburized showed a life factor of up to 10x compared to the Baseline material M50NiL and therefore were selected for the bearing test campaign. For gear testing M50NiL-DH and Ferrium C61 carburized were selected. Subscale Bearing Tests under mixed lubrication condition demonstrated the superior performance of both materials compared to M50NiL-DH (up to factor 3,3). Whereas the contamination and spall propagation performance of both materials did not reach the superior performance of M50NiL-DH. A potential way for further improvement is an additional nitriding process to increase the surface hardness and introduce higher compressive stresses which might be beneficial for contaminated conditions.

Performances of two selected gear material/heat treatment combinations were experimentally evaluated through tests on single tooth bending fatigue aimed to determine the high cycle bending fatigue strength distribution.

Tests were carried out on a single tooth bending fatigue (STBF) rig installed on a resonance machine.

The machine has a resonant frequency depending of the sample stiffness that is be around 110 - 140 Hz if the sample is a gear. Both the maximum reachable static and dynamic load are ±100kN.

The employment of a STBF rig has been preferred to a power circulating test rig:

- less amount of samples required to collect the same number of data (since with the same gear an high number of experiment can be carried out)
- high load required to observe bending failure and therefore high risk to have unwanted other damage modes (e.g. wear, scuffing, pitting) in a power circulating rig.

The design of the STBF equipment reproduces root stress conditions representative of power gearboxes and is optimized to:

- minimize the uncertainty on the applied load magnitude
- minimize the uncertainty on the position of the load application point
- minimize the uncertainty on the direction of the load (the load is perpendicular to the involute profile gear tooth at the loading location)
- avoid surface damage and sliding at the tooth – load anvil interface.

The behaviour of the whole test equipment under load has been characterized monitoring the strain conditions by means of strain gauges located in different points. Experimental data have been compared with FEA.

In particular the root stress conditions have been determined using LTCA (Load Tooth Contact Analisys) and experimentally verified by means of test execution with gears instrumented at the root fillet with strain gauges. Data have showed a good agreement.

An original approach has been identified for the statistical data analysis. The same approach has been used in order to define an optimized experimental test plan with the object to maximize the achievable results.

Activity on gears has been carried out by AM Testing, with the collaboration of the project Topic Manager, Avio Aero.

4.2 Use and dissemination of foreground

Section A (public)

TEMPLATE A: LIST OF SCIENTIFIC (PEER REVIEWED) PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
NO.	Title	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Year of publication	Relevant pages	Permanent identifiers[3] (if available)	Is/Will open access[4] provided to this publication?
1	*Scouting high performance steels for gears and bearings*	*P. Mirring*	*GREENER AVIATION 2016*	*1*	*Greener Aviation*	*Brussels*	*2016*	*11*	http://www.greener-aviation2016.com/	yes
2										

[3] A permanent identifier should be a persistent link to the published version full text if open access or abstract if article is pay per view) or to the final manuscript accepted for publication (link to article in repository).
[4] Open Access is defined as free of charge access for anyone via the internet. Please answer "yes" if the open access to the publication is already established and also if the embargo period for open access is not yet over but you intend to establish open access afterwards.

Section B (confidential)

TEMPLATE B1: LIST OF APPLICATIONS FOR PATENTS, TRADEMARKS, REGISTERED DESIGNS, ETC.			
Type of IP Rights: Patents, Trademarks, Registered designs, Utility models, etc.	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant (s) (as on the application)
n/a	n/a	n/a	n/a

TEMPLATE B2: OVERVIEW TABLE WITH EXPLOITABLE FOREGROUND					
Exploitable Foreground (description)	**Exploitable product(s) or measure(s)**	**Sector(s) of application**	**Timetable, commercial use**	**Patents or other IPR exploitation (licences)**	**Owner & Other Beneficiary(s) involved**
n/a	*n/a*	*n/a*	*n/a*	*n/a*	*n/a*

4.3 Report on societal implications

A General Information *(completed automatically when **Grant Agreement number** is entered.*	
Grant Agreement Number:	CS-GA-2014-632472
Title of Project:	Scouting HIgh Performance Steels for GEARs and
Name and Title of Coordinator:	Patrick Mirring, Head of R&D Aerospace

B Ethics		
1. Did you have ethicists or others with specific experience of ethical issues involved in the project?	O X	**Yes** **No**
2. Please indicate whether your project involved any of the following issues (tick box) :	***YES***	
INFORMED CONSENT		
• Did the project involve children?		
• Did the project involve patients or persons not able to give consent?		
• Did the project involve adult healthy volunteers?		
• Did the project involve Human Genetic Material?		
• Did the project involve Human biological samples?		
• Did the project involve Human data collection?		
RESEARCH ON HUMAN EMBRYO/FOETUS		
• Did the project involve Human Embryos?		
• Did the project involve Human Foetal Tissue / Cells?		
• Did the project involve Human Embryonic Stem Cells?		
PRIVACY		
• Did the project involve processing of genetic information or personal data (eg. health, sexual lifestyle, ethnicity, political opinion, religious or philosophical conviction)		
• Did the project involve tracking the location or observation of people?		
RESEARCH ON ANIMALS		
• Did the project involve research on animals?		
• Were those animals transgenic small laboratory animals?		
• Were those animals transgenic farm animals?		
• Were those animals cloning farm animals?		
• Were those animals non-human primates?		
RESEARCH INVOLVING DEVELOPING COUNTRIES		
• Use of local resources (genetic, animal, plant etc)		
• Benefit to local community (capacity building ie access to healthcare, education etc)		
DUAL USE		
• Research having potential military / terrorist application		

C Workforce Statistics

3 Workforce statistics for the project: Please indicate in the table below the number of people who worked on the project (on a headcount basis).

Type of Position	**Number of Women**	**Number of Men**
Scientific Coordinator (FAG)	0	1
Work package leader (FAG)	0	2
Experienced researcher (i.e. PhD holders) (FAG)	0	2
PhD Students (FAG)	0	0

Other (FAG)	2	2
Scientific Coordinator (AMT)	0	1
Work package leader (AMT)	1	0
Experienced researcher (i.e. PhD holders) (AMT)	1	2
PhD Students (AMT)	0	0
Other (AMT)	1	7

4 How many additional researchers (in companies and universities) were recruited specifically for this project?	**none**
Of which, indicate the number of men:	
Of which, indicate the number of women:	

D Gender Aspects

5	**Did you carry out specific Gender Equality Actions under the project** ?	○ X	Yes No

6 Which of the following actions did you carry out and how effective were they?

		Not at all effective				Very effective
❑	Design and implement an equal opportunity policy	○	○	○	○	○
❑	Set targets to achieve a gender balance in the workforce	○	○	○	○	○
❑	Organise conferences and workshops on gender	○	○	○	○	○
❑	Actions to improve work-life balance	○	○	○	○	○
○	Other:					

7 Was there a gender dimension associated with the research content – i.e. wherever people were the focus of the research as, for example, consumers, users, patients or in trials, was the issue of gender considered and addressed?

○ Yes- please specify

X No

E Synergies with Science Education

8 Did your project involve working with students and/or school pupils (e.g. open days, participation in science festivals and events, prizes/competitions or joint projects)?

○ Yes- please specify

X No

9 Did the project generate any science education material (e.g. kits, websites, explanatory booklets, DVDs)?

○ Yes- please specify

X No

F Interdisciplinarity

10 Which disciplines (see list below) are involved in your project?

X Main discipline[5]: 2.3 metallurgical and materials engineering

○ Associated discipline5: | ○ Associated discipline5:

G Engaging with Civil society and policy makers

11a	**Did your project engage with societal actors beyond the research community?** *(if 'No', go to Question 14)*	○ X	Yes No

11b If yes, did you engage with citizens (citizens' panels / juries) or organised civil society (NGOs, patients' groups etc.)?

○ No

○ Yes- in determining what research should be performed

○ Yes - in implementing the research

○ Yes, in communicating /disseminating / using the results of the project

[5] Insert number from list below (Frascati Manual)

11c In doing so, did your project involve actors whose role is mainly to organise the dialogue with citizens and organised civil society (e.g. professional mediator; communication company, science museums)?	○ ○	Yes No

12 Did you engage with government / public bodies or policy makers (including international organisations)

- ○ No
- ○ Yes- in framing the research agenda
- ○ Yes - in implementing the research agenda
- ○ Yes, in communicating /disseminating / using the results of the project

13a Will the project generate outputs (expertise or scientific advice) which could be used by policy makers?

- ○ Yes – as a **primary** objective (please indicate areas below- multiple answers possible)
- ○ Yes – as a **secondary** objective (please indicate areas below - multiple answer possible)
- ○ No

13b If Yes, in which fields?

Agriculture Audiovisual and Media Budget Competition Consumers Culture Customs Development Economic and Monetary Affairs Education, Training, Youth Employment and Social Affairs		Energy Enlargement Enterprise Environment External Relations External Trade Fisheries and Maritime Affairs Food Safety Foreign and Security Policy Fraud Humanitarian aid		Human rights Information Society Institutional affairs Internal Market Justice, freedom and security Public Health Regional Policy Research and Innovation Space Taxation Transport	

13c If Yes, at which level?

- ○ Local / regional levels
- ○ National level
- ○ European level
- ○ International level

H Use and dissemination

14 How many Articles were published/accepted for publication in peer-reviewed journals?	**none**
To how many of these is open access[6] provided?	**none**
How many of these are published in open access journals?	**none**
How many of these are published in open repositories?	**none**
To how many of these is open access not provided?	**none**
Please check all applicable reasons for not providing open access:	
❑ publisher's licensing agreement would not permit publishing in a repository ❑ no suitable repository available ❑ no suitable open access journal available ❑ no funds available to publish in an open access journal ❑ lack of time and resources ❑ lack of information on open access ❑ other: ……………	

15 How many new patent applications ('priority filings') have been made? *("Technologically unique": multiple applications for the same invention in different jurisdictions should be counted as just one application of grant).*	**none**

16 Indicate how many of the following Intellectual Property Rights were applied for (give number in each box).	Trademark	**none**
	Registered design	**none**
	Other	

17 How many spin-off companies were created / are planned as a direct result of the project?	**none**
Indicate the approximate number of additional jobs in these companies:	

18 Please indicate whether your project has a potential impact on employment, in comparison with the situation before your project:

❑	Increase in employment, or	❑	In small & medium-sized enterprises
❑	Safeguard employment, or	❑	In large companies
❑	Decrease in employment,	X	None of the above / not relevant to the project
❑	Difficult to estimate / not possible to quantify	❑	

19 For your project partnership please estimate the employment effect resulting directly from your participation in Full Time Equivalent (*FTE = one person working fulltime for a year*) jobs:	*Indicate figure:*
Difficult to estimate / not possible to quantify	X

[6] Open Access is defined as free of charge access for anyone via the internet.

I	Media and Communication to the general public
20	**As part of the project, were any of the beneficiaries professionals in communication or media relations?** ○ Yes X No
21	**As part of the project, have any beneficiaries received professional media / communication training / advice to improve communication with the general public?** ○ Yes X No
22	**Which of the following have been used to communicate information about your project to the general public, or have resulted from your project?**

❑	Press Release	❑	Coverage in specialist press
❑	Media briefing	❑	Coverage in general (non-specialist) press
❑	TV coverage / report	❑	Coverage in national press
❑	Radio coverage / report	❑	Coverage in international press
❑	Brochures /posters / flyers	❑	Website for the general public / internet
❑	DVD /Film /Multimedia	❑	Event targeting general public (festival, conference, exhibition, science café)

23	In which languages are the information products for the general public produced?

❑	Language of the coordinator	X	English
❑	Other language(s)		

Question F-10: Classification of Scientific Disciplines according to the Frascati Manual 2002 (Proposed Standard Practice for Surveys on Research and Experimental Development, OECD 2002):

FIELDS OF SCIENCE AND TECHNOLOGY

1. NATURAL SCIENCES

1.1 Mathematics and computer sciences [mathematics and other allied fields: computer sciences and other allied subjects (software development only; hardware development should be classified in the engineering fields)]

1.2 Physical sciences (astronomy and space sciences, physics and other allied subjects)

1.3 Chemical sciences (chemistry, other allied subjects)

1.4 Earth and related environmental sciences (geology, geophysics, mineralogy, physical geography and other geosciences, meteorology and other atmospheric sciences including climatic research, oceanography, vulcanology, palaeoecology, other allied sciences)

1.5 Biological sciences (biology, botany, bacteriology, microbiology, zoology, entomology, genetics, biochemistry, biophysics, other allied sciences, excluding clinical and veterinary sciences)

2 ENGINEERING AND TECHNOLOGY

2.1 Civil engineering (architecture engineering, building science and engineering, construction engineering, municipal and structural engineering and other allied subjects)

2.2 Electrical engineering, electronics [electrical engineering, electronics, communication engineering and systems, computer engineering (hardware only) and other allied subjects]

2.3. Other engineering sciences (such as chemical, aeronautical and space, mechanical, metallurgical and materials engineering, and their specialised subdivisions; forest products; applied sciences such as geodesy, industrial chemistry, etc.; the science and technology of food production; specialised technologies of interdisciplinary fields, e.g. systems analysis, metallurgy, mining, textile technology and other applied subjects)

3. MEDICAL SCIENCES

3.1 Basic medicine (anatomy, cytology, physiology, genetics, pharmacy, pharmacology, toxicology, immunology and immunohaematology, clinical chemistry, clinical microbiology, pathology)
3.2 Clinical medicine (anaesthesiology, paediatrics, obstetrics and gynaecology, internal medicine, surgery, dentistry, neurology, psychiatry, radiology, therapeutics, otorhinolaryngology, ophthalmology)
3.3 Health sciences (public health services, social medicine, hygiene, nursing, epidemiology)

4. AGRICULTURAL SCIENCES
4.1 Agriculture, forestry, fisheries and allied sciences (agronomy, animal husbandry, fisheries, forestry, horticulture, other allied subjects)
4.2 Veterinary medicine

5. SOCIAL SCIENCES
5.1 Psychology
5.2 Economics
5.3 Educational sciences (education and training and other allied subjects)
5.4 Other social sciences [anthropology (social and cultural) and ethnology, demography, geography (human, economic and social), town and country planning, management, law, linguistics, political sciences, sociology, organisation and methods, miscellaneous social sciences and interdisciplinary , methodological and historical S1T activities relating to subjects in this group. Physical anthropology, physical geography and psychophysiology should normally be classified with the natural sciences].

6. HUMANITIES
6.1 History (history, prehistory and history, together with auxiliary historical disciplines such as archaeology, numismatics, palaeography, genealogy, etc.)
6.2 Languages and literature (ancient and modern)
6.3 Other humanities [philosophy (including the history of science and technology) arts, history of art, art criticism, painting, sculpture, musicology, dramatic art excluding artistic "research" of any kind, religion, theology, other fields and subjects pertaining to the humanities, methodological, historical and other S1T activities relating to the subjects in this group] .