harmLES

Final Report (Del 5.4)

Publishable Summary to SESAM

Document No:	harmLES-Del 5.4
Issue Revision:	1.3
Date:	21/04/2015
Prepared by:	All, compiled by Ernst-Dieter Janotka, Andreas Merstallinger

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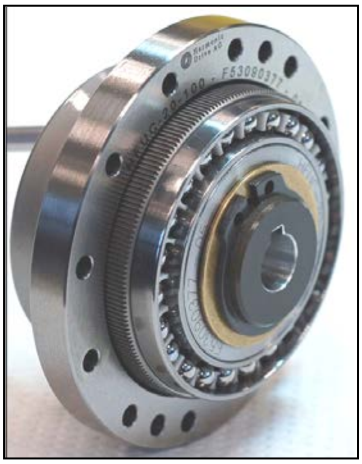
1 HARMLES AND ITS PROGRESS BEYOND STATE OF THE ART



Harmonic Drive® gears are used for more than four decades for space applications. In fact, this gear principle was originally developed for space applications. This does cover both planetary exploration and satellites. Based on the application, a large variety of configurations has been developed over time, following as well the product improvements achieved. Today, gears from size 5 (12.7 mm pitch circle diameter, PCD) to size 100 (254 mm PCD) are available in gear ratios ranging from 30:1 to 320:1 and in different types such as cup type, flat type, large hollow shaft type and lightweight versions.

Harmonic Drive® gears are based on the same, unusual principle of a flexible element used to transmit torque. That offers the following advantages: they provide low or zero backlash in combination with excellent precision. The large gear ratio in combination with the ability of zero stick-slip movement at slow speeds makes them an often used choice for space applications: a small actuator motor (meaning low mass and low power consumption) may be used to move large components like antennas or solar panels. Currently, most of those gears are used in grease lubricated condition, whereas this is always linked to the risk of outgassing and limits significantly the operational temperature (range of -40 to +70°C).

Before harmLES, in order to increase the temperature range, trials to apply solid lubricants to Harmonic Drive® gears, as commonly used for e. g. bearings, were performed. It is known that for US applications, the usage of gold and lead-plated Harmonic Drive® gears was for a long time state of the art. These coating are known as being poor compared to current dry lubrication concepts. Representatives of the same family of soft coatings are MoS2 and WS2. Both coatings have been applied to Harmonic Drive® gears. Especially in the beginning a proper bonding between the coating and the base material was difficult to achieve and resulted in early loss of the lubricant, being practically scrubbed off. Another challenge is that MoS2 does not perform properly under atmospheric conditions as the humidity in the air changes the tribological contact. WS2 is somewhat more forgiving but does not show similar performance under vacuum conditions. WS2 has shown good results in different cryogenic applications but does lack in the stability of the process as it is currently applied manually. Major differences between different suppliers (all licensed under the trade name Dicronite®) have been reported.

These coatings have been applied to Harmonic Drive® gears and it was shown, that such gears can be operated even at -269°C. Anyhow, although being used in various cryogenic applications, the reachable endurance was very short – typically only few hundred output revolutions were achieved. Hence, harmLES (having been started in 2011 and finalized in 2015) was aiming to increase the accessible lifetime by developing a new Harmonic Drive® gear type for solid lubrication. Knowing, that the current gear design was ideal for grease lubrication, an integrated approach was chosen considering materials, coatings and gear design. Therewith, besides the development of a proper coating, a major aim of the project was to optimize the geometry of the Harmonic - Drive® gear especially towards the needs of solid lubrication for space applications. Based on requirements raised by potential end – users, the Harmonic Drive® gear was re – designed and a new gear type called ZirconLine of size 20 with ratio 100 was developed. Throughout the project, measures were step – by step introduced to the gear, decreasing as well the contact stresses and the sliding path especially within the toothing. Finally the prototype of a gear size 20 ratio 100 with a new tooth profile was manufactured. The characteristics of the gear were in line with the requirements raised by the end users, which were mainly zero backlash, a minimum stiffness of $1.1*10^4$Nm/rad and a Transmission Accuracy better than 60 arcsecs. The reachable endurance within vacuum was increased significantly from a few hundred output revolutions to more than 17,500 revolutions. Figure 1-1 depicts the course of the efficiency monitoring for the developed prototype – it remained constant throughout the entire test.

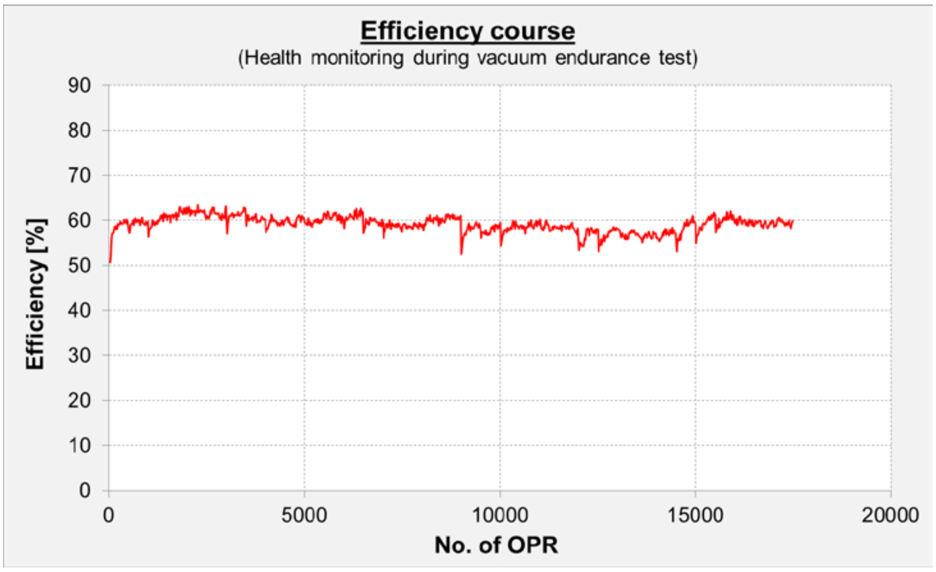


Figure 1-1: Efficiency monitoring during vacuum endurance test

This result achieved within the vacuum endurance test was confirmed by the posttest inspection of the gear. As shown in Figure 1-2 (left), the gear stiffness after the test is identical to the initial pre-test value – indicating a successful completion of the test. The visual appearance of the toothing is depicted in Figure 1-2 (right). It was found in very good condition after the test which underlines the huge progress made within the project.

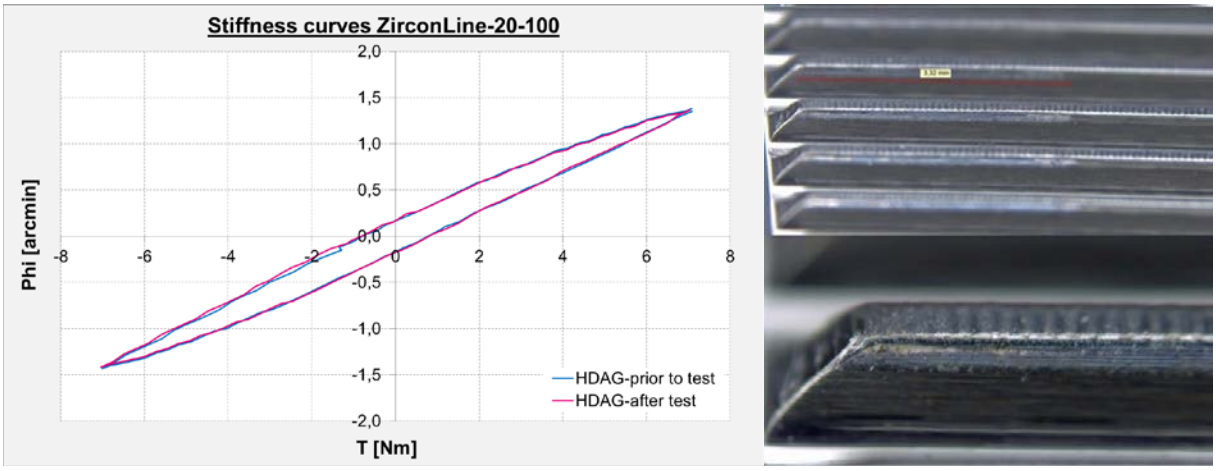


Figure 1-2; left: Stiffness curve prior to and after the test; right: Toothing of the Flexspline after the test

Besides the re-design, the success was also based on a new coating originally developed by TECNALIA. This is a composite coating based on a WC-interlayer plus a solid lubricant top-layer being a reinforced MoS_2. Already during development on basis of simple discs being relevant to the materials and surface roughness of the gears, it was seen that this composite coating showed superior lifetime compared to standard MoS_2 coatings. The coating process was adopted to gear components (toothing and WG-bearing). Finally, several gear sets were coated and tested. For the final gears, the characteristics of the gear were in line with the above mentioned requirements. This result could be approved by the visual appearance and microscopic investigation by SEM. Figure 1-3 compares the situation at beginning of harmLES with the final achieved promising lifetimes. No wear was visible, the coatings were working well on gear level.

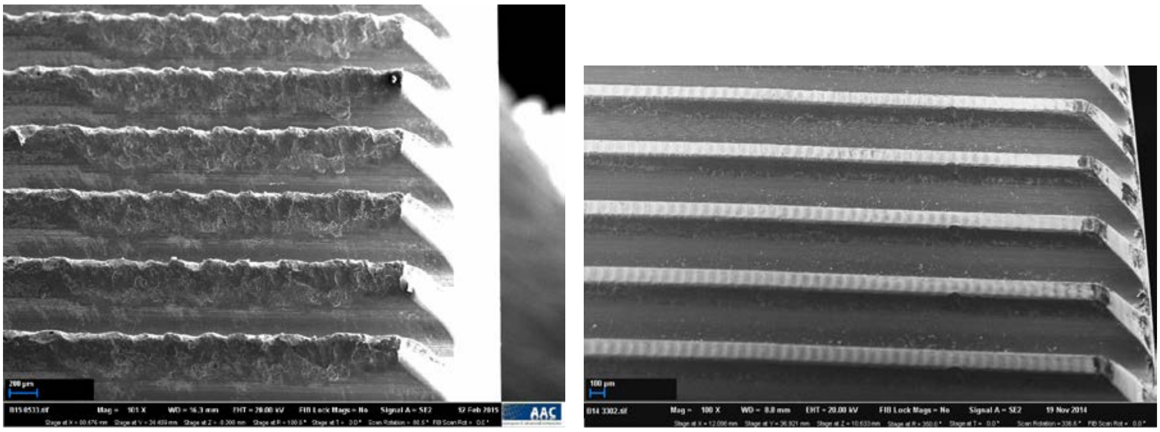


Figure 1-3: Left: Worn toothing at beginning of harmLES   Right: Still no wear after 17500 OPR

Overall harmLES enabled for the first time solid lubricated Harmonic Drive® gears with zero backlash and high gear stiffness providing reasonable endurance. Summarizing the following achievement can be stated:

- Lifetime of more than 17,000 output revolutions at 4Nm were achieved in vacuum testing (Compared to a few hundreds at begin of the project).

HarmLES outcome	→ HD size 20 ratio 100
	• Zero backlash
	• TA < 60 arcsec
	• Output torque: 4Nm
	• Endurance: 17,000OPR
	• Stiffness > 11000 Nm/rad

Figure 1-4: Achievements of harmLES

2 PUBLISHABLE SUMMARY (SESAM)

2.1 Publishable summary

Harmonic Drive® gears are used for more than four decades for space applications. In fact, this gear principle was originally developed for space applications. This does cover both planetary exploration and satellites. Based on the application, a large variety of configurations has been developed over time, following as well the product improvements achieved. Today, gears from size 5 (12.7 mm pitch circle diameter, PCD) to size 100 (254 mm PCD) are available in gear ratios ranging from 30:1 to 320:1 and in different types such as cup type, flat type, large hollow shaft type and lightweight versions.

Harmonic Drive® gears are based on the same, unusual principle of a flexible element used to transmit torque. That offers the following advantages: they provide low or zero backlash in combination with excellent precision. The large gear ratio in combination with the ability of zero stick-slip movement at slow speeds makes them an often used choice for space applications: a small actuator motor (meaning low mass and low power consumption) may be used to move large components like antennas or solar panels.

A *specification* for such a gear was setup on basis of a questionnaire to European end-users. The transmission accuracy shall remain below 60arcsecs as specified for terrestrial gears. The repeatability is specified with a maximum of 3arcsecs. The minimum gear stiffness is foreseen to be at a level of approx. $1.1*10^4$ Nm/rad which is close to the stiffness of a HFUC gear size 20. Beside quantitative properties, a main qualitative feature of the Harmonic - Drive® gear is seen in the zero backlash, which is a decisive advantage compared to other gear types. The lifetime was required with 17,000 output revolutions at an output torque of 4Nm.

Within harmLES, the geometry of the Harmonic - Drive® gear could be optimised towards solid lubrication for space applications. This resulted in a new gear type called ZirconLine of size 20 with ratio 100. Throughout the project, measures were step – by step introduced to the gear, decreasing as well the contact stresses and the sliding path especially within the toothing. Finally the prototype of a gear size 20 ratio 100 with a new tooth profile was developed.

Besides the re-design also a new coating could be developed by TECNALIA. This is a composite coating based on a WC-interlayer plus a solid lubricant top-layer being a reinforced MoS_2. During development on basis of simple discs, an optimum variant could be achieved, which showed superior lifetime compared to standard MoS_2 coatings on the steels being relevant to the Harmonic - Drive® gear. The coating process was adopted to gear components (toothing and WG-bearing). Finally, several gear sets were coated and tested. For the final gears, the characteristics of the gear were in line with the above mentioned requirements. This result could be approved by the visual appearance and microscopic investigation by SEM. No wear was visible, therefore the test could be evaluated to be passed.

HarmLES enabled within its duration to increase the achievable endurance of the gears, whereas the characteristics of the prototypes were in line with the above mentioned requirements:

- at 4Nm lifetimes of even up to 20.000 output revolutions were achieved in vacuum testing (partly without failure at end of test, compared to a few hundreds at begin of the project).
- in contrast to grease lubricated HDs, the efficiency course of the gear during the vacuum endurance test was almost stable throughout the whole test !

2.2 Description of the project context and the main objectives (max 4 pages)

Harmonic Drive® gears are used for more than four decades for space applications. In fact, this gear principle was originally developed for space applications. This does cover both planetary exploration and satellites. Based on the application, a large variety of configurations has been developed over time, following as well the product improvements achieved. Today, gears from size 5 (12.7 mm pitch circle diameter, PCD) to size 100 (254 mm PCD) are available in gear ratios ranging from 30:1 to 320:1 and in different types such as cup type, flat type, large hollow shaft type and lightweight versions.

Harmonic Drive® gears are based on the same, unusual principle of a flexible element used to transmit torque. That offers the following advantages: they provide low or zero backlash in combination with excellent precision. The large gear ratio in combination with the ability of zero stick-slip movement at slow speeds makes them an often used choice for space applications: a small actuator motor (meaning low mass and low power consumption) may be used to move large components like antennas or solar panels.

The main drawback for the use of Harmonic Drive® gears is that they presently need liquid lubricants (including greases) in order to satisfy the operational requirements. Due to vacuum and temperature in space, liquid lubricants and greases bear the risk of outgassing and evaporation. This leads on one hand to loss of lubrication efficiency (some components are lost in the lubricant), but on the other hand to depositions of these outgassed products on other sensible surfaces. Thereby, optical components might be degraded. This may even lead to loss of a full mission, e.g in earth observation.

Since 2002, there has grown a demand for dry lubricated gears due to various needs. These cover extended temperature ranges and applications with critical items close to the gear like optics or telescopes. Harmonic Drive AG has increased its effort in supporting space applications by installing a dedicated team of engineers for these demanding applications. This was based on the need defined by the customers to receive a broader and more profound support and the necessity to adapt the products more to the specific applications. Over the years, this did allow to pool a lot of application experience but being as well faced with more demanding requirements. In the last years, the need for providing more and more customisation and support did increase and the number of inquiries based on the request of using dry lubrication became more apparent. However, no sufficient solutions could be given on durability and suitability of such a dry lubrication scheme and the customers were left alone with the qualification risk.

The project is application triggered. The members of the consortium – manufacturer of Harmonic Drive® gears, developer of coatings and a material developer having a contract as “space materials testhouse” – are on one hand closely related to the space market and its applications. They know also the related requirements for use in space, but act also in non-space markets. This enables “spin-in”, i.e. bringing in of concepts from other fields.

The main research need follows the limited success to use “commercial off the shelf (COTS)” coatings, as a result from previous projects and efforts. The project shall overcome the problems in the low endurance of dry lubricated Harmonic Drive® gears by primarily improvement of dry lubricant coatings and necessary design modifications on the gear. Herein, composite coatings with MoS_2 as main solid lubricant but having additional constituents are seen as a most promising option for soft coatings, while Hydrogenated diamond-like carbon (DLC) films are a good candidate for hard coatings.

As outlined in the proposal, the objectives of harmLES were the following:

The major technical objectives of the harmLES project can be summarized as follows:

- Understand the wear mechanisms, that lead to early failures in present dry lubricating coatings
- To develop coatings which enable long life times in Harmonic Drive® gears.
- Re – design of the Harmonic Drive® gear towards the needs for dry lubrication
- Re-assess the materials presently used in the Harmonic Drive® gears, for better mechanical support of coatings
- Establishment of a coating process ready to be qualified for space applications
- Validate dry lubricated Harmonic Drive® gears for long life time by field tests under thermal vacuum
- Install a user-group to setup requirements for future missions

The most promising concepts which will be targeted prepared during harmLES are:

- Solid lubricant coatings based on MoSx-WC (<3µm) prepared by PVD.
- Solid lubricant coatings applied on thermal diffusion treated substrates to improve load-bearing capability.
- Application of an interlayer prior to the solid lubricant coating to increase adhesion.
- Optimisation of the coating thickness and lay-up to get maximum endurance life.

The consortium decided not to include "one or the other" end user, but is targeting to serve the whole European space industry. Therefore, a so-called end-user-group was installed. Several European End-users from space industry took part in specifying requirements for Harmonic Drive® gears in order to meet demands for future missions. Letter of Interests (LoI) were attached to the proposal showing the interest of space industry.

The industrial objectives guide the choice of coating processes (PVD) and the compositions towards long life time of Harmonic Drive® gears in space applications. The major (industrial) objective of the harmLES project is to improve performances in the following applications:

- Establishment of new generation of dry lubricated Harmonic Drive® gears with proper life time
- Improvement of Life Time from currently a few output revolutions to several hundred with the target of several thousands
- Establishment of new coating for Harmonic Drive® gears (to be transferred to industrial coaters)

Improved lifetime opens automatically the number of applications which can be served by this:

- a few output revolutions are sufficient for launchers and deployment mechanisms (solar panels, …)
- several hundred output revolutions will open the application to planetary exploration and scientific applications
- several thousand output revolutions are then sufficient for antenna pointing mechanisms, thruster vectorisation mechanisms, antenna pointing mechanisms first on Low Earth Orbit and the upper end of output revolutions even for geo-stationary satellites.

The need for advanced dry lubricated Harmonic Drive® gears is driven by the space industry. The need is:

- No dry lubricated Harmonic Drive® gears are available on commercial market,
- Strategic1: "Non-dependence from US suppliers", i.e. being not dependent on export restrictions (ITAR)
- Strategic2: Solution of this problem would lead to European and even world-wide leadership
- New: Harmonic Drive® gears could be used in non-ambient temperatures
- New: No risk of contamination of sensible parts of spacecrafts (outgassing)
- Spin-offs into similar, industrial applications such as vacuum applications (semiconductor industry, large tests stand such as DESY) and cryogenic application (which is a growing industrial sector) are clearly visible.

2.3 Description of the main final S&T results / foreground

As planned, at beginning of the project a workshop was organised together with an end user group (European space industry). Following that, the requirements for Harmonic Drive® gears were established.

The project was setup in two lines running partly in parallel:

- development of coatings based on sample level
- development on component level

The development of coatings based on sample level was started with a survey of coatings and the selection of "Starters" (COTS and a space proven coating by TECNALIA) was done. After manufacturing of Lab-samples by HDAG, TECNALIA prepared first coatings and did structural characterisation like XRD and scratch testing. HDAG purchased reference coating from commercial suppliers. Testing of these coatings was performed by TECNALIA and AAC on tribometer level including post-inspection by SEM. AC2T investigated the surface chemistry on these coatings by XPS, as well as on components from previous projects as benchmark. The developed coatings were benchmarked with dry lubricant coatings based on MoS_2 and DLC (commercial and prototype) and WC (commercial).

Main findings on sample level are that benchmark testing showed that the most promising solid lubricant coating is based on MoS_2 being reinforced with WC, being referred to as "MoS_2-WC". Alternatives e.g. based on DLC, WS2 or WC did not offer reasonable lifetimes (<10.000 cycles). For the actual application based on high strength steels like SS17-4PH, even standard (pure) MoS_2 coatings offer lower lifetimes (range <50.000 revs) than MoS_2-WC coatings: repeatability by TECNALIA shows a "repeated lifetime" over 200.000 revs, but tests at AAC under vacuum achieved more than 700.000 revs. Among the variations in process parameters and layup, an optimum coating type (with reference "25988") was identified as the most promising with regard to endurance. Also changes in the interface (thickness/gradient) did not show significant improvement of endurance. Besides that, an increased subsurface strength seems to further increase lifetime, which was shown by fretting and PoD-tests under vacuum.

Besides coating properties, also the substrate plays an important role. First tests on MoS_2-WC coatings failed because of the high roughness of the substrates (Ra<0,6µm). This initiated a change the machining of the gear components using new machining parameters and revealing in lower "medium" roughness in range of Ra = 0,1-0,4µm. The achieved roughness on the gear components was the one applied to discs. It was finally proven to be the optimum range with regard to lifetime of the MoS_2 –WC coatings. Tribological tests on coatings applied on samples with medium roughness showed significantly increased lifetimes in contact to pins relevant to Harmonic Drive® gears. When testing those coatings on polished gear steel life time decreased. Even further increase in lifetime of the MoS_2-WC coatings on samples was obtained, after performing pre-treatment of the steel surface. This leads to improved mechanical support of the solid lubricant coating. The findings were transferred stepwise to the second line, i.e. onto the gears.

Second line was the development on component level, i.e. gear parts were coated with the new coating types and tested. This second line was split again in two paths: influence of coating types (thickness, compositions, pre-treatment) but also influence of gear design. Also these lines were followed in parallel, taking findings of the coating development into account. As first step (prior to testing of the gears itself), the test devices at HDAG and AAC were upgraded: it was needed to establish a kind of stiffness testing which can be done in-situ in the vacuum chamber, as the efficiency alone was not sufficient to assess the condition of the Harmonic Drive® gears. While upgrading the test devices, the re-design of the Harmonic Drive® gear was started with a detailed FEM-simulation. These findings were introduced step-by-step to the gear components. After testing in air and vacuum, wear was investigated by SEM (AAC) and XPS (AC2T).

Besides the gear development also the test devices needed upgrades, which were already used for testing the gear components. Especially, the ability to measure in-situ the stiffness was used to assess the integrity of the gears. In order to ease testing, a so-called “standard test box” was utilized. This was used to just change the main gear components (Flexspline, Circular Spline and Wave Generator bearing) without the need to build a complete gear with housing. Measurement of axial forces enabled to verify proper assembly of the test gear, as well as the assessment of the friction coefficient between FS and WGB outer ring.

The main outputs are prototypes of optimized solid lubricated Harmonic Drive® gears, which showed increasing lifetime with more development steps implemented.

First tests using the new coating failed very early, after few hundreds of revolutions. Increasing the thickness did not help. Then a first step of the re-design of the gears was finalised and inserted to the components. Then life times in the order of magnitude of few thousands of output revolutions were achieved with dry lubricated gears. The main conclusion was that changes in coating thickness do not improve life time but design changes (leading changes in geometry, contact pressure, internal preload) do lead to significant increases in life time. As a further step, the lubrication of the Wave Generator bearing was improved: the races were coated with MoS_2, which lead to a significant improvement of the gears efficiency. In parallel, a next step in design was done. As final design changes a new tooth profile in combination with a decreased gear preload showed high influence on the life time. (Such a decrease of life time when increasing the contact pressure was also seen in pin-on-disc tests, and is well known for MoS_2 based coatings.) With that, lifetimes in the range of the requirements were firstly achieved: gears were stopped at 17.500 and 22.000 revolutions without having failed. Changes in coating, e.g. thicker coating did not led to significant improvements. Also pre-treatment of the Circular Spline (although without the last step on design change) improved the performance, but not as significant as the final design change did. For WP 4, the joining of both developments (latest design plus pre-treatment) was introduced.

The final work package had the objective to merge the findings from WP 3 which means a combination of the latest design with the pre-treatment of the surfaces. However, initial tests with pre - treated, uncoated parts at HDAG showed some anomalies. Even a second trial did not lead to successful initial testing on gear level, leading finally to the decision to omit the pre-treatment. On the other hand, the pure MoS_2 in the WG-bearing was replaced by a reinforced MoS_2-WC. At last, also the design was slightly changed (i.e. the engagement of the toothing). Two demonstrators were finally assembled for testing under vacuum. The first failed before achieving 17.500 OPRs. As main reason, the WG-bearing was identified. Therefore, on short hand in the second demonstrator the WG-bearing was replaced by a pure-MoS_2 coated one. Testing was extended also to low temperature (-150°C) which would never be possible by grease lubrication.

Main output was that 2 demonstrators were finally tested under thermal vacuum. Some more gears were manufactured, but they had to be ruled out, after the initial testing under air showed no proper operation. It had to be concluded that pre-treatment of the new toothing could not be successfully introduced. Hence, for both gears no pre-treatment was selected. Further improvement of this process would be necessary before applying it. Secondly, in the WG-bearing the use of the (pure) MoS_2 was found to be the better choice, as the MoS_2-WC failed before 10.300 output revolutions. The second gear, showed promising high efficiency (~80%). This did not decrease too much when running at -150°C to ~50% (grease lubricated gears cannot go below a range of -50 °C, as the greases turn into solid-type condition that makes relative motion between parts impossible as it acts as a sort of glue. A gear would get stuck). Finally, it failed around 5700 OPR with decrease in efficiency and stiffness. This leads to the conclusion that the last design change was self-defeating with regards to the endurance and that in order to further increase the lifetime alternative solutions need to be considered.

In brief, the project claims to have been successful. It could be shown that the selected coating concept (reinforced MoS_2) enabled the best reasonable lifetimes on the steels used in Harmonic Drive® gears. Based on simulation several changes in the design were evaluated step-by-step to optimise the Harmonic Drive® gears towards solid lubrication. Finally, for a set of prototypes, the lifetime could be increased from a few hundred output revolutions to the required 17.500 and even more. Two gears were stopped without failure, indicating that even higher endurance might be feasible.

2.4 Final results and their potential impact

For space activities one of the main European strategies is "non-dependence". In the past several missions were in danger, because products which were not available from European suppliers had to be bought from US-suppliers, but export was blocked by ITAR-regulations. ITAR is a permanent danger to European space activities. Hence, it is one of the top-priorities in ESA-Programs. Moreover, if the project is successful, Europe would reach world-wide leadership in this specific product.

Economic impact is seen in two ways: in sense of entities like industry and researchers, but also in terms of "public money". European space programs are financed by public bodies (e.g. member states of ESA, EU). One major part in satellite costs are the costs for launch. Typical price range is 10.000 to 15.000 €/kg. That's why mass decrease is one of the main design drivers in space. Using Harmonic Drive® gears instead of planetary gears enable mass decreases by factors of 2 to 3. Assuming a medium harmonic gear box with a mass of 1 kg, the cost reduction is already in a range of 10.000€ to 20.000€ per unit. Consider new planetary exploration missions with a rover for low temperatures (jovian moons) or high temperatures (mercury). A rover similar to the mars rover would use 9 Harmonic Drive® gears, this would save in total 9kg, i.e. more than 90.000€ launch costs. This means, that space programs can be made more cost efficient and the tax money can be re-directed to social issues.

Second economic impact, is of course the improvement of European industry. Space market is a world-wide market. Leadership or USP have to be gained in world-wide competition. This project would definitely enable such a world-wide-USP. HDAG would become the only supplier world-wide of these high-end dry lubricated Harmonic Drive® gears gears. Other low-technology solutions with much, much lower performance (and therefore not usable for most of the applications described in the proposal) are existent. The project will ensure that HDAG is able to protect these high-end solution against attempts from outside Europe, which do enter into the low-demanding applications. So it will protect European competitiveness in a high-value market.

This will also be a sustainable strengthening and be held for several years close to a decade, since space industry is strongly relying on so-called "space heritage": the first successful product will be bought for several years, therefore future competitors will not easily enter the market. Besides industry (HDAG as supplier of the product), also researcher will benefit from the project: TECNALIA as supplier of a new coating (in terms of reputation as developer but also in terms of selling this coating in terms of spin-offs, licensing, ..), also AAC benefits from this project as being proven partner for validation of mechanisms with Harmonic Drive® gears and will gain its position as space materials testhouse in contract to ESA/ESTEC.

The results of this project will in second level also *strengthen the competitiveness of European space industry*. Companies like Astrium, Sener, Kongsberg … will be able to offer new mechanisms to satellite manufacturers. Moreover, spin-offs into similar, industrial applications such as vacuum applications (semiconductor industry, large tests stand such as DESY) and cryogenic application (which is a growing industrial sector) will follow. Further fields could even be the machining sector, where attempts are made to reduce of cutting lubricants. By improving the competitiveness of industry, ***employment is secured in Europe*** and dependence on USA or Japan is reduced.

3 MORE DETAILED DESCRIPTION OF S&T RESULTS

3.1 Main findings from WP 2 "coating development":

The WP 2 was focused on the improvement of the reinforced solid lubricant coating. The main conclusion relevant to the project's progress from WP 2 are:

- Deposition procedure is good enough to ensure the minimum quality of the MoS_2-WC based coatings. Several batches were produced with the type 25988. The reproducibility among all 25988 processes is good enough. Dispersion is as expected for MoS_2 based coatings.
- Different kind of MoS2-WC coatings where synthesized, varying thickness and P_{MoS2}/P_{WC}, however no evidence of clear endurance improvement was observed when compared to the 25988 coating
- Different kind of MoS_2-WC coatings where synthesized, varying thickness of WC and gradient layer however no evidence of endurance improvement was observed. No influence on endurance when changes in Top layer Bias compare with standard 25988 process. Hence, standard type 25988 is kept as most promising coating.

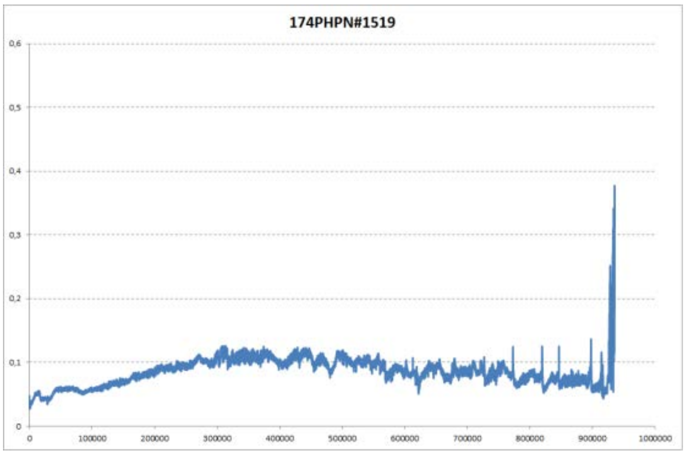


Figure 5- 1: Friction curve for a coating 25988#1519 on pre-treated steel 17-4PH against ball of 440C. Load 5N, v=0.5 m/s, ambient pressure, RH=10%.

- Based on min-life-time requirement of 200.000revs, the process can be regarded as being stable, repeatability is given.
- No influence on the durability after cleaning with isopropyl alcohol (10 min).
- Dependence of the durability on substrate material is clearly observed: pre-treatment is an advantage, highest endurance is measured when testing against the 440C polished pin.
- Applying the WC-interlayer is clearly improving lifetime.
- The endurance of the pure MoS_2 ESTL coatings is lower compared to the endurance of the pure MoS_2 coated by TECNALIA tested under the same conditions. Both are lower than the reinforced MoS_2-WC.

- Decrease on durability and friction coefficient when increasing the contact stress. The MoS_2-WC coating shows better endurance than the MoS_2 coating at medium to low contact stress (≤ 0.91 GPa). Endurance gets similar for both at high contact stresses (1.72 GPa).

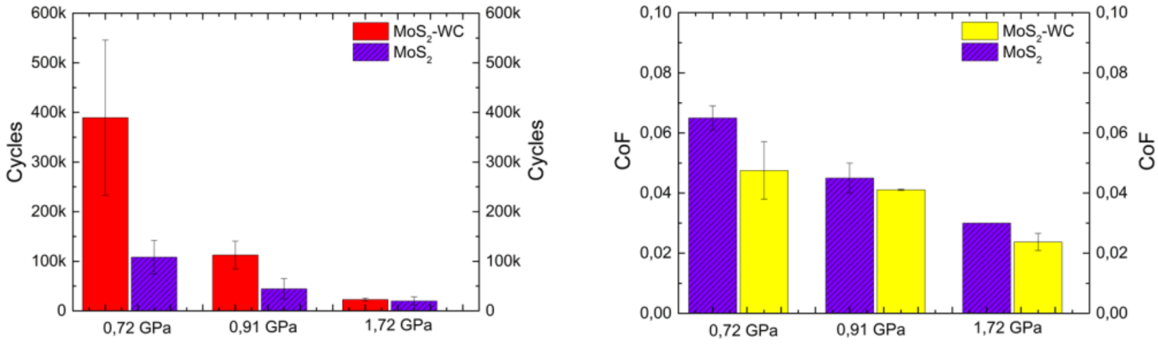


Figure 5- 2: Endurance (left figure) and CoF (right figure) measurements at different contact stress comparison between MoS_2-WC and pure MoS_2 coatings against 440C discs with Ra < 0.025 µm.

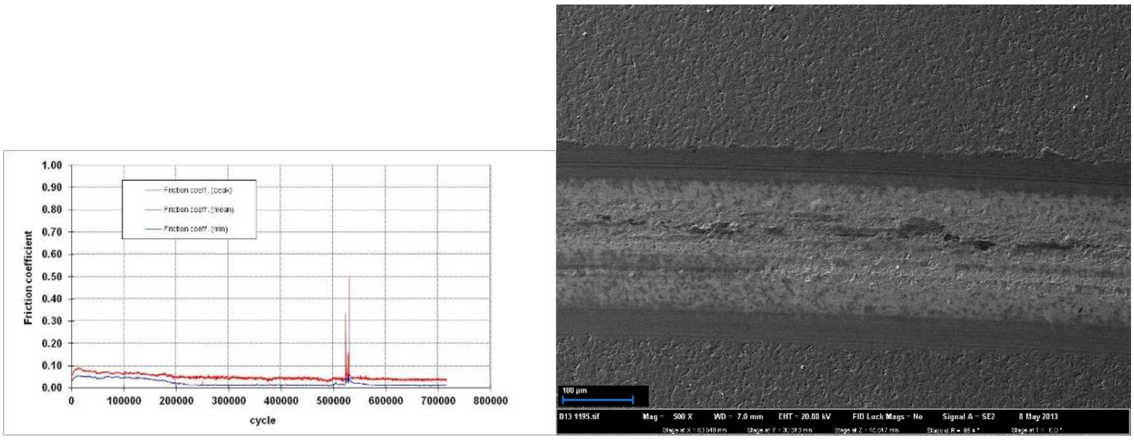
Following the result from the vacuum friction tests (PoD) at AAC, it can be concluded

- that MoS_2-WC (reinforced MoS_2) is still the most promising candidate for application in gears. Friciton and fretting tests showed both increase of lifetime when the MoS_2 is reinforced. Beside the review of TECNALIA on commercial DLC coatings, an additional review in prototype DLCs by AAC did not show any promising alternative candidate.

- that a surface roughness with about Ra=0.6µm is too high to enable proper solid lubrication (and reasonable lifetime), and that the final range of roughness of Ra~0,1-0,3µm shows best endurance (this is in well correlation to tests done by TECNALIA on hard steel, where too smooth surfaces are also disadvantageous). Finally, this range of roughness was chosen for the toothing in the gears.

- that a pre-treatment of the gear steel (SS17-4PH is quite soft compared to the bearing steels) might be recommended: fretting tests have shown that pre-treatments drastically improve fretting resistance. The friction tests herein indicate a similar trend for sliding motion. Type 25988 when applied without pre-treatment (batch #1494) shows poor lifetime, but same coating on batch #1519 (with a pre-treatment) shows definitely best performance.

- that the coating with the best endurance under vacuum (>700.000 cycles) is the type 25988 #1519.



- *Figure 5- 3: Plot of friction (left figure) and SEM-image of the track (right figure) of a coating type 25988 under vacuum against SS15-5PH with Ra ~ 0.2 µm. This test was stopped manually without failure and shows a very good lifetime (>700.000 cycles. Inside the track a lot of MoS_2 is still available, detected with EDAX. In the SEM image the edges show no breaking off, which indicated good adhesion.*

- that the repeatability of this coating on (soft) gear steel is still an issue, as the subsequent batches #1897 and #1940 with nominally similar type 25988 show less lifetimes (although friction is comparable). The reason for this is not yet clear, but it seems to be related to the steel substrate (SS17-4PH). Discs were from different manufacturing batches, so variation between batches could be the reason. Because, similar tests done by TECNALIA on polished AISI440C steel against AISI440C balls show proper reproducibility.

- BUT: in the batch #1897 (type 25988), also discs not being pre-treated but only having been passivated were coated: their performance (tested in an ESA-project) is comparable to the batch #1519.

- using standard (pure) MoS_2 -coatings will not enable similar high lifetime on the steel SS 17-4PH . Pure MoS2 coatings provided by TECNALIA are in same (low) range of lifetime as commercial ones procured from ESTL (Tests done in HDGSA_P23). The range of lifetime at PoD testing is about 30.000 cycles (order of magnitude less than for reinforced coatings).

- TECNALIA investigated variations in the coating type: for the pre-treated SS17-4PH in contact to non-treated SS15-5PH, besides the standard 25988#1519, only one variant shows similar long life-times at PoD testing: 26007 #1619 having a thicker WC-interlayer.

Hence, from PoD tests done in vacuum in oscillating motion, finally the initial standard coating type 25988 can be recommended for later use in components.

It is also concluded that a roughness in range close to Ra~0,2µm is required (which fits well to the actual machining of the toothing).

Finally, a pre-treatment of the (quite soft) SS17-4PH steel is at least strongly recommended.

4 DETAILS ON RESULTS

4.1 Main findings/Summary of WP 3 (Component development):

4.1.1 Upgrade of test rigs

At HDAG, a test rig is implemented to perform an endurance test with constant speed and constant output torque. The maximum torque level during the test is 25Nm, the input speed needs to be between 50 and 500rpm. Based on the end user requirements the parameters for the first tests are fixed to a constant load of 16Nm at a speed of 250rpm. Additionally to transmission accuracy and stiffness, the axial force and the efficiency of the test gear need to be supervised for health monitoring. The two latter – mentioned are measured on the harmLES test rig, whereas the measurement of the efficiency has been implemented subsequent, allowing a continuous monitoring of this parameter. The axial force is, as transmission accuracy and stiffness, measured after distinct periods by applying an output torque ramp between 10 and 25Nm at a constant speed of 100rpm.

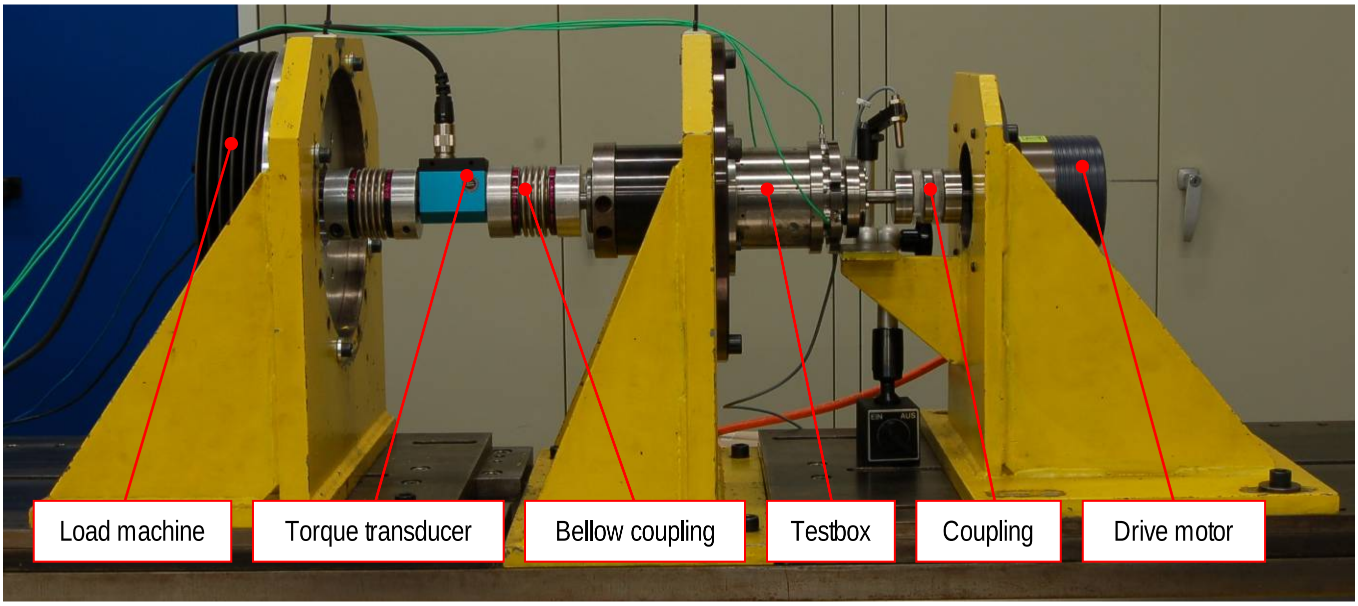


Figure 4-1: Drive train; elements of drive train fastened on stiff connectors

Within Task 3.1 it was also part of AAC to upgrade its test-devices for Harmonic Drive® gears towards the vacuum suitable testbox used by HDAG. The upgrades enabled finally to test Harmonic Drive® gears not only for efficiency, but also for decrease in stiffness. (See Figure 4-2.)

Reasons for needing the upgrade:

- Due to the user requirements of a higher output-torque, it was necessary to improve the stiffness of the shafts in order to transmit up to 40Nm.
- To reduce the length of the measurement-line inside the vacuum-chamber new couplings were installed to compensate possible radial and angular deviation.

- For the HDAG-Testbox new input- and output-shaft adapters were necessary.
- A "blocker for the input shaft inside the vacuum chamber" was implemented, it enables to measure the stiffness of the gear during life testing (i.e. without breaking vacuum).
- In a second step, a replacement of the angular sensors was done to improve the angular resolution, towards high-precision angular-sensor which will then be 11840 increments per rotation, resulting in a resolution of 2,74".

There are four properties for characterization of the HD. In the following there is a short description which parts of the assembly will be used for each measurement.

- Measurement of stiffness
- Measurement of transmission accuracy
- Measurement of axial-force
- Measurement of efficiency

Figure 4-2: AAC SALOTTE: test rig for harmonic gears under thermal vacuum (running at low temperature, seen by iced feed lines for the liquid nitrogen)

4.1.2 Optimisation of Design

The optimization of the gear design is done in various steps, whereas the general approach is shown in Figure 4-3. Within WP 3, the development steps were performed in two different paths, which is on the one hand the path called "gear development" on the other hand the path assigned as "coating development (on gear level)". With regard to the gear development, this path contains again several steps of gear optimisations. Finally, the findings are merged to an optimized gear version within WP 4 which combines the most promising findings from WP 3.

Starting with the Benchmarking, a gear with standard industrial design was used to identify the feasible performance of an unchanged gear type. The results which were gained throughout air and vacuum testing were evaluated based on a dedicated FE – analysis as well as on a detailed simulation of the gears kinematic. With the identification of potential measures to improve the gears performance in dry lubricated condition, design changes were implemented in various steps, whereas due to time constraints some steps were performed in parallel.

Regarding the "coating development" the initial idea was, to keep the gear design unvaried and to identify the potential improvement by only varying the coating e. g. in terms of thickness, support layer or composition. After a first set of tests and based on the results of the FE – Analysis it was found that this approach is a dead end, as the design of the gear is ideal for liquid lubrication but not for dry lubrication. Thus, the reachable endurance is fairly short and the path was resigned. The focus was set mainly to the design change of the gear.

With respect to the design changes, all measures introduced took in to account the requirements concerning the most important gear characteristics raised by the end users. These are the backlash – freedom, a minimum stiffness of $1.0*10^4$ Nm/rad and a Transmission Accuracy of less than 60arcsecs. Along all the introduced design changes, these requirements could be fulfilled. Within Task 3.3 a first step was undertaken (Adaptation of geometry 1.1), with the aim to lower the contact stress especially within the toothing. With this first step a significant increase in the gears lifetime could be achieved, and therewith this approach was further developed in the second introduced optimisation step which is the "Adaptation of geometry 1.2".

As within the WP 2 one recommendation was to introduce a pre- treatment to the Harmonic Drive® gear prior to coating, another change of the gear configuration was performed in such a way, that the geometry from the first step was kept identical and that a pre – treatment was introduced to the gear (Adaptation of geometry 1.1 & pre -treatment). Again, as mentioned in chapter 2.3 another step towards the target of 17,500OPR was made. Finally within WP 3 the most significant modification with respect to the gears geometry was performed in the "Adaptation of geometry 2". A new tooth profile was introduced, and the gears' kinematic was adopted respectively. This was combined with the decrease of the gears preload which was has already shown to be beneficial for the endurance. With this modification, prototypes were subjected to vacuum endurance testing showing the best results so far.

Based on the findings within in WP 3, the final gear configuration was fixed. Initially the approach was to merge the gear design of the second geometric adaptation with the pre – treatment that was used for the "Adaptation of geometry 1.1 & pre - treatment". Anyway, after testing this configuration under air in uncoated condition with oil – lubrication it had to be realized, that the configuration did not work properly. A deeper investigation on the failure cause would be necessary, which was not possible in the given time frame. Therefore, the final gear version remains without pre – treatment.

As testing within WP 3 showed that still a slight improvement with regard to the tooth engagement was possible, for WP 4 a slight modification with regard to the kinematic was introduced. Finally the main changes between the last set of gears tested in WP 3 and WP 4 has to be seen in the variation of the coating, as the coating thickness was adopted based on positive results on gear level. Especially with respect to the WGB, it was decided to go for the reinforced coating at least for one of the test gears.

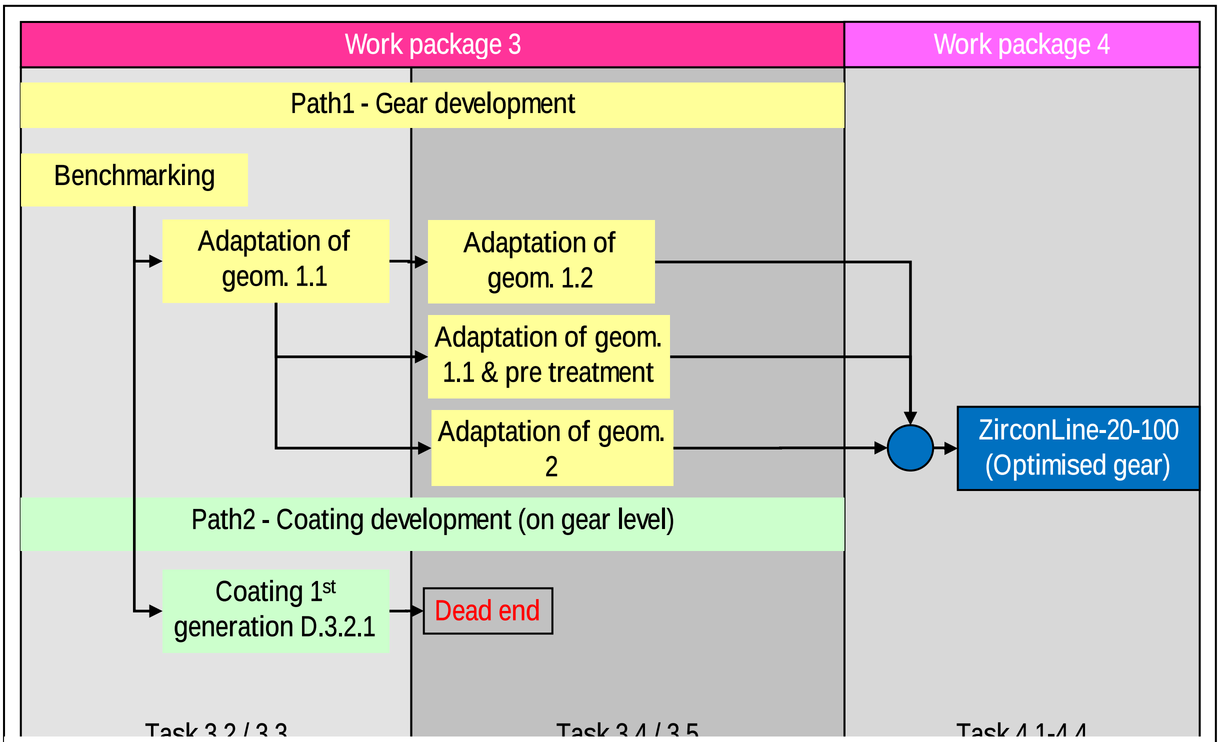
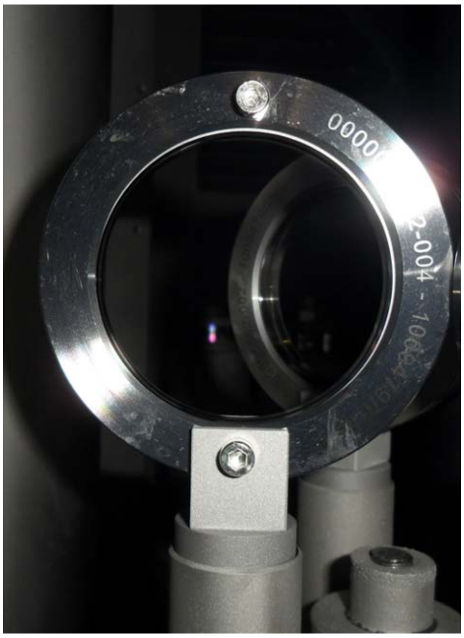


Figure 4-3: Development logic

4.1.3 Coating of components

The coating synthesis was performed in a CC800/8 CemeCon PVD unit. Previous to deposition the components were cleaned in an ultrasonic bath with a detergent and rinse with deionised water. Then, the components were introduced in the vacuum chamber until a pressure of 2 mPa was reached. The position of the components in the chamber configuration can be seen on Figure 4-4. The deposition process started with resistive heating of the chamber followed by a plasma etching process in Ar at -120 V bias voltage.

As mentioned above, WP 3 focused on development of components. Some images from the coating process are shown in Figure 4-4.



Outside outer ring | Inner side outer ring | Outer side of the inner ring

Figure 4-4: *Configuration chamber for WG components: left image outside outer ring, centre image belongs to Inner side outer ring and right image Outer side of the inner ringCoating thickness along the different components of the Harmonic Drive® Gears was studied in dummy parts by X-SEM. Taking into account those results deposition time was adjusted to obtain a nominal coating thickness of the component varying from 1.5 to 1.8 microns.*

Coating process control

Polished 440C discs as well as partially masked silicon wafer strips were also included in the chamber in each coating process. After coating deposition, the process (coating) was validated by measuring the adherence, hardness and tribological properties (pin-on-disc) of the coating deposited onto polished 440C disc. Besides, the thickness of the coating on flat surfaces was also measured by contact profilometry onto partially masked silicon wafer strip (flat surface).

As an example the endurance obtained by the pin-on-disc test (440C disc (Ra≤ 0.02µm) vs. 440C ball (d=6mm, *Figure 4-5*.

Quality control tribological tests show low friction values (CoF= 0.06-0.07) in all the process. This is in agreement with the CoF of 0.06 we obtained when testing the reference MoSx-WC (25988#1519). The variation in endurance is connected with the thickness variation obtained in the AISI 440C steel.

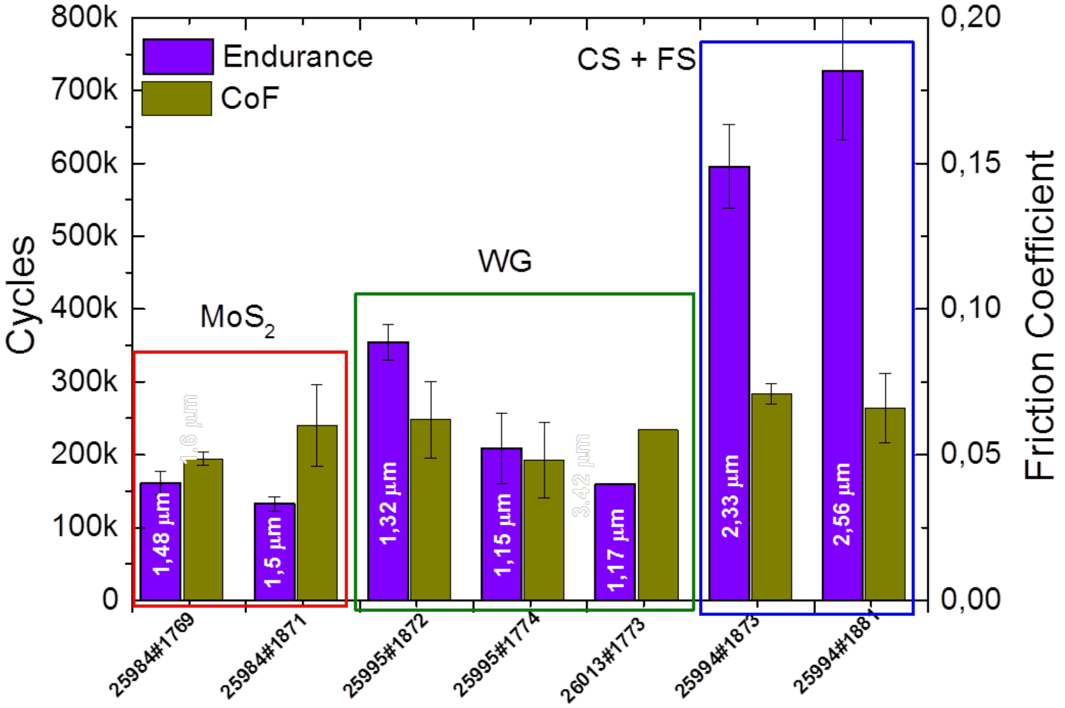


Figure 4-5: Endurance and CoF measurements on flat discs of polished (Ra <0.02) 440C for quality control of component process for components coated in 3rd period, with 440C balls of 6 mm diameter, 5N of load, speed of 0.5 m/s and 10% of relative humidity. The thickness of each coating is also detailed in the figure.

4.1.4 Main findings/Summary of WP 4 (Demonstrator testing):

Table 4-1 shall combine the brief summary of the findings within the post-test analysis of the tested gear together with the post-analysis by SEM. With regards to the gear characteristics, the focus is set on the gear stiffness K1 (stiffness close to the zero – crossing), the Transmission Accuracy and the wear condition of the toothing. As additional information the test duration is listed in the table below. Additionally a short note from the SEM investigation is shown: green background states the surface to be in good condition (depletion zones are regarded as good). Single isolated wear features (like small scars) are identified with light orange background. Advanced wear is highlighted orange.

As mentioned before, the upper part of the table shows that with the introduced optimization measures the test duration increases, whereby the amount of wear within the toothing decreases. So far, SEM investigations confirmed, that the toothing is the critical interface since the WGB races are coated with (pure) MoS_2 (from Harm#8 to Harm#13. Moreover it can be seen that the wear is more sever on the FS than on the CS (#10 to #12). Very first scars (isolated locations on the tooth flank with lost coating) are not visible in the mechanical performance (stiffness, efficiency, TA): this is seen in #10 (interim) and #12 at end of the test. Harm#20 also shows good contact surface with just an isolated wear scar on the upper edge of toothing of the FS.

The outer side of the WGB is in good condition (therefore it is concluded that also the FS-I does not show exposed steel surfaces). A few spots with peeling off / depletion were still seen. This means, that the I/F between WGB and FS is not critical.

WGB races were initially just treated with Dicronite, which was not sufficient for life time lubrication. Starting from Harm#8, the WGB races were coated with (pure) MoS_2 and then performed well: the WG-bearing showed no wear and was in good condition after test. The races of those WGBs just showed typical thinning (referred to as depletion), which is most pronounced on the inner race close to major axis (both sides). All surfaces were found still to be well covered with solid lubricant. Finally, some optimisation of the adhesion might be targeted (single spots with peel-off, also beside the contact area). But overall, the WGB works well.

Based on the results achieved in WP 3, the final gear configuration was fixed and introduced to Harm#20. Beside a slight modification of the gear kinematic, the coating thickness was varied based on the finding for Harm#13. For the bearing races MoS_2/WC with a WC-interlayer was used instead of pure MoS_2 as for the gears Harm#10 to #13 a thinning of the coating was found. The actually chosen process did not perform well, the test was stopped after 10,300OPR and the races showed advanced wear after test. Their morphology is similar to the initial ones with too less lubricant when using Dicronite. Hence, for the moment, the WGB should preferably coated with pure MoS_2.

Of course, test results on sample level showed the MoS_2-WC coating to have higher endurance than pure MoS_2 also on hard bearing steel. However, further optimisation of the process towards use in the WGB is necessary and might be envisaged (probably on adhesion combined more elasticity as the WGB-outer race is permanently deflected, and actually the interlayer showed peel-off. Such a behaviour was not seen on the steels of the toothing.).

Therefore it was decided to continue the testing in the frame of WP 4 with a WGB with pure MoS2 coated races for Harm#21. Within this test beside the endurance testing at room temperature a phase of operation at deep temperature (-150°C) was introduced. The gear performed well during the cold cycle with increased gear stiffness. Beside this, the efficiency was measured for various operating points at room temperature and it was shown that there is neither a dependency on the speed nor on the output torque for the considered ranges between 50 and 250rpm and 4 to 12Nm load. The measured efficiency is comparably high with more than 80%.

Anyway, the test was stopped prematurely after 5,700OPR, as lubrication failed within the toothing.

Finding on	ZirconLine V1.2			ZCL V1.3	ZirconLine V2.2			ZCL.V3.2	
	Harm#06	Harm#07	Harm#08	Harm#11	Harm#10	Harm#12	Harm#13	Harm#20.	Harm#21
Stiffness K1	degrad.	degrad.	degrad.	unvaried	degrad.	unvaried	unvaried	degrad.	degrad.
Transmission Accuracy	degrad.	degrad.	degrad.	degrad.	degrad.	unvaried	unvaried	degrad.	degrad.
Test duration [OPR]	4,500	620 [@16Nm]	3,000	9,500	13,500	22,000	17,500	10,300	5,700
Toothing (visual)	wear	Wear	wear	wear	wear	onset of wear	no wear	Onset of wear	wear
SEM at	EOL	EOL	EOL	EOL	Interim 10.000	EOT	EOT	EOL	EOL
FS									
CS									
FS-i									
WGB-o									
WGB-or									
WGB-ir									

Table 4-1: Summary post - test analysis

4.1.5 Final conclusion

Within the harmLES – project, overall 11 different gear versions were designed and manufactured. Seven of these versions were subjected to vacuum endurance test, whereas overall 14 vacuum tests have been performed at AAC. From the beginning on, the main focus within the project was set towards the reachable endurance of the gear, as this seemed to be the most challenging aspect. The gear geometry was varied step by step while keeping the main requirements highlighted by the end users community which were:

- Zero Backlash,
- Minimum stiffness of $1.1*10^4$Nm/rad,
- Transmission Accuracy below 60 arcsec.

Besides the geometric adaptation of the gear, based on the results gained within the coating development, various versions of the MoSx/WC coatings were applied to the gear in order to allow a proper lubrication of the component set. To be able to conclude on the development performed in the frame of the harmLES – project an overview on the achieved endurances within the vacuum endurance tests throughout the different gear versions shall be given. A respective depiction is shown in Figure 4-6. The different gear version, their assignment to the different Tasks and the reached endurances are presented.

Starting with the industrial gear version (gear type CobaltLine) for the Benchmarking gear and the coating variation, fairly short operating times of less than 100OPR were achieved. With the introduction of a first geometric change for the ZirconLine V1.1 an increase in the endurance to a few 1,000 output revolutions was realised. This first step was further developed with the version 1.2, where additionally the MoS2 coating for the WGB races was introduced. The endurance of the gears was again advanced to values between 3,000 and 4,500 OPR. By introducing an additional pre - treatment to V1.1, the ZirconLine V1.3 was created, whereby another step towards the target of 17,500 output turns was performed. 9,500 revolutions were achieved with this gear version. At the end of WP 3, the new tooth profile combined with lower gear preload was realised within the ZirconLine V2.2. The possible number of output revolutions increases to between 13,000 and 22,000 revolutions, whereas two of the gears passed the target of 17,000 turns. Therewith, it was shown, that at room temperature a lifetime of 17,500 revolutions at a load of 4Nm is principally makeable with a backlash free Harmonic Drive® gear.

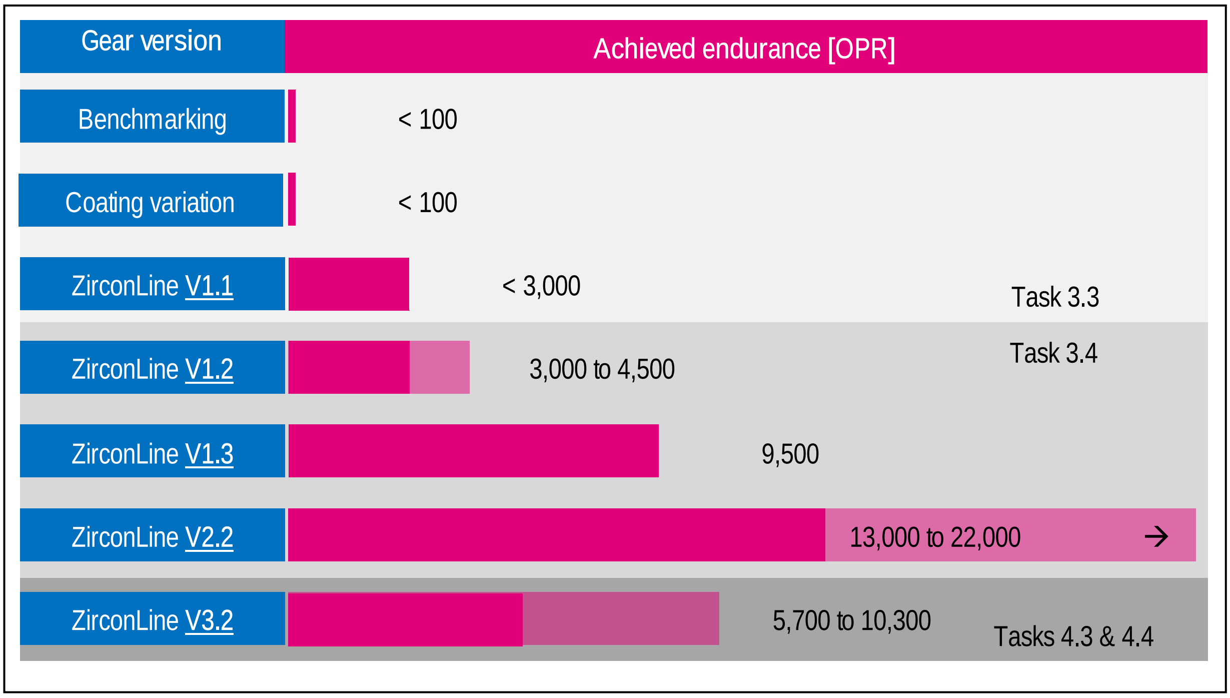


Figure 4-6: Gear versions and achieved endurance (→ means that EOL was not reached)

Within WP 4 another step forward with regards to the development of dry lubricated Harmonic Drive® gears was intended. Therefore the knowledge gained throughout all the tests in WP 3 was merged to a final gear version. Based on the results of the tests performed under air, finally the gear version ZirconLine V3.2 was subjected to vacuum endurance test. Within these tests it was shown that the gear is suitable for operation at deep temperatures (-150°C). Furthermore it was shown, that at room temperature high efficiencies of more than 80% are possible. Anyway, the endurance achieved with the V3.2 is comparably short to those received with the version 2.2. Obviously, with the introduction of the last optimisations the development was exaggerated at a certain point.