HARMLES – DEVELOPMENT OF DRY LUBRICATED HARMONIC DRIVE® GEARS FOR SPACE APPLICATIONS

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1. ABSTRACT

Harmonic Drive® gears are used in several space flight mechanisms such as SADM's or pointing mechanisms. Main reasons for choosing the gears are advantages like zero backlash, high gear stiffness and high transmission accuracy. Nowadays typically grease lubrication is used, whereas this is linked to the risk of outgassing and limits the operational temperature.
In order to increase the temperature range, trials to apply solid lubricants to Harmonic Drive® gears, were performed. Based on these trials it was found that the gears can be operated even at -269°C. Anyhow, although being used in various cryogenic applications, the reachable lifetime is comparably short. So as to improve the achievable endurance an essential development was necessary. Hence the EU – funded project HarmLES was executed in order to significantly increase the accessible lifetime. Following an integrated approach covering gear design, materials and coating, the prototype of a new Harmonic Drive® gear type was developed.

2. REQUIREMENTS ON GEAR LEVEL

The Harmonic – Drive® gear today is in its geometry optimised towards grease lubrication for terrestrial applications. So far the approach for the use in space was to rely generally on this gear design, whereas materials and lubricants are substituted by space feasible products. This works very well for numerous grease lubricated space applications. Anyhow, driven by the similar design (e.g. tooth shape) the gears are often oversized with respect to their mechanical properties, whereas regarding the special tribological demands the design provides potential for improvements. Therefore, the possibility to reduce mechanical properties leaves the opportunity for an optimisation of the gear design especially towards the needs of dry lubrication.
Before starting the development, requirements for the new gear type were assessed. Therefore an end user survey was performed, where customers were asked for their needs based on a gear of size 20. The results are given in Table 2-1.
It shall be mentioned that the requirements with regards to transmission accuracy and repeatability are the same as for the standard Harmonic Drive® gear, whereas the stiffness for a gear size 20 is slightly relaxed. The zero backlash as a main quantitative feature, shall be kept. Based on the experience the intended operation duration of 17,000 OPR in combination with zero backlash is a demanding goal.

		Unit	Value
Char-acteristic	Transmission Accuracy	[arcsec]	60
	Repeatability	[arcsec]	6
	Stiffness	[Nm/rad]	$1.1*10^4$
	Zero Backlash	-	Yes
Per-formance	Output torque	[Nm]	4
	Endurance	OPR	17,000
	Temperature Range	[°C]	-200 to 150

Table 2-1: Requirements on gear level

3. DEVELOPMENT APPROACH ON GEAR LEVEL

The HarmLES - project is seen as an integrated approach covering as well the gears' geometry but also material and coating. The development of an adopted coating as well as the assessment of alternative gear materials is performed based on laboratory trials like e. g. common PoD tests, fretting – tests, scratch tests etc. The results are used for a selection of configurations that are to be tested on gear level.
The gear development itself is seen under two aspects. This is primarily the geometric optimisation, but also the introduction of the developed coating on gear level. The initial intention was to follow the two

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aspects in parallel paths. Anyway, it was found early that working with an unchanged gear design was a dead end and the path was skipped. Testing of the adopted coatings was introduced to the path of gear development. Figure 3-1 depicts a schematic of the subsequent development steps.

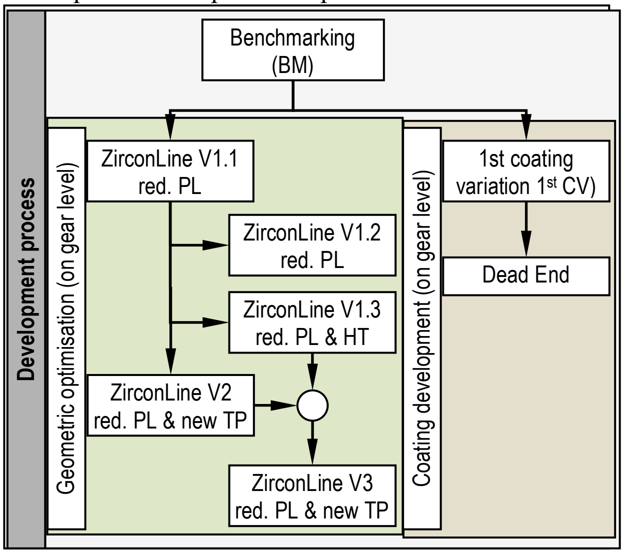

Figure 3-1: Schematic depiction of development approach.

The chosen approach aims for a step – by – step implementation of the modifications. This enables a deep understanding of the impact of each variation. Based on the comprehension of the various influences, a transferability of the results to further gear sizes and ratios is given.

According to Figure 3-1 the starting point for the development was a benchmarking with a space suitable standard gear size 20, ratio 100 (BM). In a first step, the gear preload was reduced for version 1.1 and 1.2 (red. PL). This was complemented by a heat treatment (HT) of the base material for version 1.3. In a next step additionally a new tooth profile (new TP) was introduced to version 2. Finally the gained knowledge was merged to the gear version 3. At least one sample of each gear version was subjected to a vacuum endurance test to verify the impact of the respective modification. The result is the prototype of a new gear type ZirconLine-20-100.

4. ANALYSIS AND SIMULATION

Besides the test based verification of the impact of different modifications, also profound analysis of the tribological contacts was performed. Hertzian contact stress as well as sliding path within the toothing were assessed and compared between the different gear versions. With the quantification of the mentioned parameters, the transferability of the test results to further gear sizes and ratios gains in reliability.

Being aware that the critical tribological contacts within the gear are the toothing and the contact between Flexspline (FS) and Wave Generator bearing outer ring (WGB OR) (ref. to [1]), the focus for the simulation was set on theses contacts. The peak Hertzian stress was assessed based on FE – modelling. The sliding path within the toothing can be determined via a Matlab – tool allowing a 3 – dimensional simulation of the tooth engagement.

	Peak Hertzian stress [MPa]		
	toothing	FS / WGB	WGB
Benchmarking gear	2000	1200	2100
ZirconLine V3	730	380	1400

Table 4-1: Peak Hertzian stress for benchmarking gear and ZirconLine V3

In the course of the project various calculations were performed, whereas in this frame for reasons of clearness only the results for the benchmarking gear and the final gear version shall be compared. The peak Hertzian stress for an output torque of 4Nm is given in Table 4-1.

The results clearly show that for the considered operating point the standard gear provides significantly higher stresses which primarily originate from the internal gear preload. Due to the geometric modifications, the preload is reduced for the new gear type which causes a decrease in the maximum stress. It shall be mentioned that this effect is visible for low and medium external loads only. With increasing output torque the proportion of the external load on the contact stress becomes dominating which overrides the impact of the internal preload.

A comparison of the sliding path within the toothing is given in Table 4-2. A reduction of more than 50% was achieved by the introduction of the new tooth profile and the modified kinematic of the tooth engagement.

	Sliding path [mm]	
	Per tooth mesh	Per OPR
Benchmarking gear	0.1	20
ZirconLine V3	0.045	9.0

Table 4-2: Sliding path within the toothing for Benchmarking gear and ZirconLine V3

5. GEAR TESTING

5.1. Approach and test parameters

As mentioned in chapter 3 at least one gear of each version was subjected to a vacuum endurance test, whereas procedure and test parameters remained broadly identical throughout the entire project.
The life tests were performed using a standardised vacuum suitable test-box for the integration of the gear. Assembly of the gear and pre – test characterisation were accomplished by Harmonic Drive. Afterwards, the entire test-box was shipped to AAC in Austria for the execution of the vacuum endurance test, with the following parameters:

Temperature:	24°C (-150°C for the final gear version)
Pressure:	<10^{-5}mbar
Input speed:	250 min-1
Output torque:	4Nm
Load profile:	constant
Rotational direction:	cw (view on output shaft)
Orientation test gear:	vertical (Wave Generator up)

The health monitoring was performed via the efficiency, which was continuously recorded for the entire test duration. It shall be mentioned, that for the monitoring the parasitic torques of input and output support bearings were not considered, as only a change of this characteristic should be detected – a decline by 20% was fixed as failure criterion. Besides the efficiency also gear stiffness and transmission accuracy were assessed after distinct intervals to support the health monitoring.
Following the endurance testing, the characterisation of the gears was repeated at HDAG in the same way as prior to the test. This was followed by a detailed visual inspection of the parts, which was complemented by SEM and EDX Analysis performed at AAC if necessary.

5.2. Gear configuration and lubrication

The gear materials for Flexspline (FS) and Circular Spline (CS) are 15-5PH cond. H1075 and 17-4PH cond. H1150. Previous PoD testing did not show the necessity to deviate from this standard. As WGB a hybrid bearing was chosen, made of X30CrMoN 15 1 races and Si_3N_4 balls, as the combination of ceramic and steel promises tribological advantages for dry lubrication. The cage is made of Tecasint® 1391, which is a MoS_2 containing Polyimide (PI) material that has been identified as potential European sourced retainer material for dry lubricated bearings [2] if use at high temperatures is envisaged. The chosen materials remained identical throughout the entire project. Regarding the lubrication, the applied coatings differ for the tribological contacts.
Knowing that the critical contact is the toothing, the reinforced MoS_2-WC coating was used for the teeth from the very beginning. The coating type for the toothing remained principally the same for all the tested samples, whereas, driven by the advancement in coating development, the configuration varied. Therewith, especially for the last gear versions (V2 and V3) properties like e.g. coating thickness, thickness of interlayer, proportion between MoS_2 and WC were adopted.
The reinforced MoS_2-WC coating shows better endurance compared to pure MoS_2 coating especially at lower contact stresses (see Figure 5.2-1).

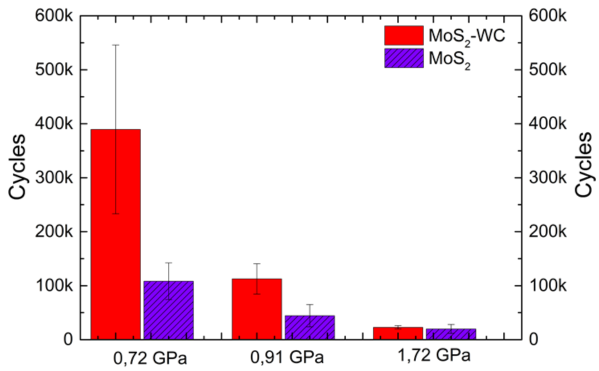

Figure 5.2-1: Coating endurance measured in the pin-on disk test at different contact stressed (ball: 440C, substrate material: polished 440C, R.H.=10%, speed 0.5 m/s)

In addition, friction coefficient showed lower values for the reinforced MoS_2-WC coating compared to pure MoS_2. On the other hand, friction coefficient decreases when increasing the contact stress (see Figure 5.2-2).

Therefore, the reinforced MoS_2-WC is a suitable solid lubricating coating for the Harmonic Drive® gears.

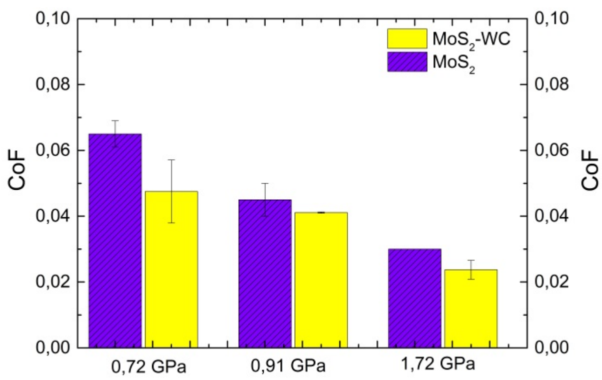

Figure 5.2-2: Friction coefficient measured in the pin-on disk test at different contact stressed (ball: 440C, substrate material: polished 440C, R.H.=10%, speed 0.5 m/s)

For the contact between FS and WGB a similar approach as for the toothing was followed. The reinforced MoS_2 coating was applied from the very beginning and again properties were adopted for the last gear versions.

Gear version	Coating reference or designation			
	Teeth CS / FS	FS - ID	WGB OR	WGB
BM	25994		25995	DL5
1st CV	25996		25997	DL5
V 1.1	25994		25995	DL5
V 1.2	25994		25995	DL5
	25994		25995	MoS_2
V 1.3	25994		25995	MoS_2
V 2	25994		25995	MoS_2
	26016 / 26017	26017	25995	MoS_2
V 3	26022 / 26017	26017	26017	MoS_2

Table 5.2-1: Coating reference / designation for the different tribological contacts.

Regarding the WGB, initially balls and races were coated with Dicronite®DL5. It should act as initial lubrication, providing low friction during run – in, until MoS_2 from the bearing cage is transferred to balls and races. As it was found within the first tests (ref.to [1]) that the strategy did not provide low friction, the coating was changed to MoS_2.

Table 5.2-1 gives an overview on the used coatings for the various tribological contacts, whereas either a reference number or the coating designation is provided. The given reference numbers identify the respective configuration of the MoS_2-WC coating.

5.3. Gear characteristics

Introducing geometric optimisations in order to increase the reachable lifetime necessarily affects on the gear characteristics, especially the gear stiffness. With regards to the requirements raised by the end users (ref. to chapter 2) a compromise between zero backlash, high gear stiffness and long lifetime needs to be realised. This target was supported by the chosen step – by – step approach as not only the impact of the modifications on the lifetime but also on gear stiffness and zero backlash is evaluable.

The results of the pre – test characterisation[1] of the different gear versions are given in Table 5.3-1. The characteristics of the component sets version 1 are summarized as they follow a similar approach with regards to their geometric modification.

Looking on the gear stiffness K1 (which is the stiffness close to the zero crossing) it is visible that with the introduction of the modifications a relaxation occurs. Whereas for the unchanged geometry the stiffness is at a level of $1.9*10^4$ Nm/rad, it reduces to $1.3*10^4$ Nm/rad for the gears V1 and V2 which is in accordance with the requirements (ref. to Table 2-1). Only the last version deceeds the limit slightly. Regarding the transmission accuracy, the situation is identical. The component sets fulfil the needs, whereas only the last version exceeds the boundary value slightly.

Gear version	Gear characteristics		
	Stiffness (K1) [Nm/rad]	TA [arcsec]	Zero backlash
BM	$1.9*10^4$	55.8	Yes
1st CV	$1.9*10^4$	42.6	Yes
V 1	$1.3*10^4$	36.2	Yes
V 2	$1.3*10^4$	39.5	Yes
V 3	$0.9*10^4$	62.5	Yes

Table 5.3-1: Results of pre - test characterisation

Referring to the requirement of zero backlash, which is one of the most important qualitative features of the Harmonic Drive® gear, all the versions comprise this characteristic. Examples for stiffness curves of a Benchmarking gear, a gear of version 2 and a gear of version 3 are shown in Figure 5.3-1. Two main objectives are clearly visible – the trends of the curves show the zero – backlash and the decrease in the gear

[1] Note: The given values are mean values as typically more than one gear per version was manufactured.

stiffness with the advanced introduction of geometric modifications.

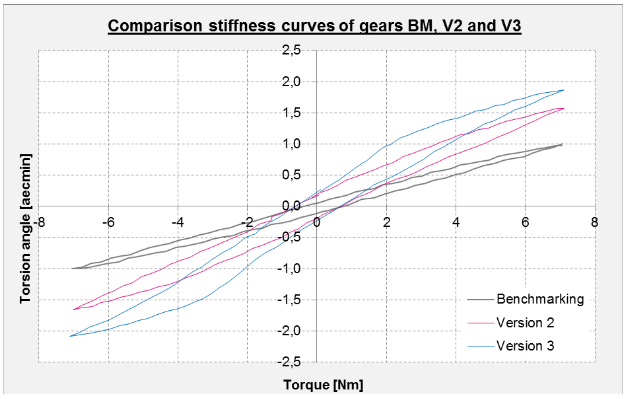

Figure 5.3-1: Stiffness curves of the different gear versions

5.4. Results of vacuum endurance testing

Following the characterisation, the vacuum durability tests were performed. Test results for gears from versions BM, 1st CV and V1.1 (ref. to Figure 3-1) have already been presented in [1]. Only the main conclusions shall be repeated briefly:

- The reachable lifetime with the unchanged gear design is a few output revolutions only.
- The introduction of a reduced preload lead to an increase in endurance to a few thousand revolutions.
- The lubrication of the WGB with Dicronite® DL5 is not satisfying.

Related to the last point, MoS_2 was introduced as coating for the WGB. It was firstly used for a gear V1.2. Figure 5.4-1 shows a comparison of the efficiency[2] monitored throughout the durability test for two gears of version 1.2; one lubricated with DL5, one with MoS_2. The result is obvious – due to the use of MoS_2 the efficiency increases by 20%.
According to Figure 3-1 the next step in development was the introduction of an additional heat treatment. In a first single test, the endurance could be further increased to 9,500OPR. This positive effect of the heat treatment could not be confirmed in the further course of the project.

Being aware that the reduction of the gear preload, which mainly lowers the Hertzian stress within the tribological contacts, has a positive impact on the endurance, the next modification was made. With the introduction of a new tooth profile, the sliding path was decreased for the gear version 2. According to Table 5.2-1, firstly the same MoS_2 / WC coating as for the former gear versions was used, whereas 2 gears of this configuration were subjected to test.

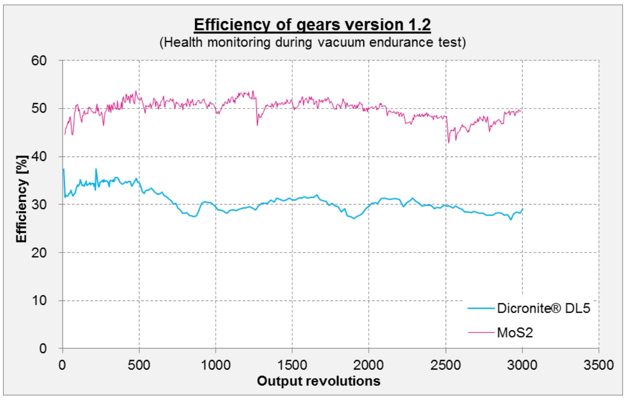

Figure 5.4-1: Efficiency of gears V1.2, WGB coated with Dicronite®DL5 or MoS2

For both gears, the results of the efficiency monitoring are shown in Figure 5.4-2. The reached lifetime has increased to between 13,000 and 22,000 OPR. The reason for the variation in lifetime is given in the gear stiffness. The one with the shorter lifetime is at a level of $1.3*10^4$Nm/rad, the one with the longer endurance is at only $0.9*10^4$ Nm/rad, which is below the requirements raised by the end – users.

In order to increase the load bearing capability the coating for the third gear of version 2 was varied (ref. to Table 5.2-1) especially with regards to the thickness. Although providing a stiffness of $1.5*10^4$Nm/rad, as shown in Figure 5.4-3, the aspiration of 17,000 OPR was achieved. The gear characteristics like zero-backlash, stiffness and transmission accuracy remained unchanged throughout the entire test. The visual inspection after the test confirmed the result, the tribological contacts of the gear were found in good condition. Therewith the requirements set in chapter 2 were firstly achieved for operation in vacuum at room temperature.

[2] Note: For the efficiency monitoring the parasitic torques of i/p and o/p support bearings are not considered.

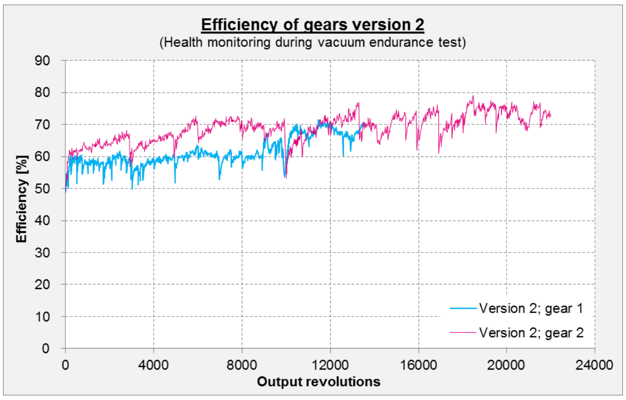

Figure 5.4-2: Efficiency course of gears version 2.

In the last development step, it was intended to merge the gained knowledge to a final gear version and to achieve further advancement with regards to the endurance. Therefore the gears geometry was once again slightly modified and the coating configuration was varied (ref. to Table 5.2-1). For the final test, besides pure endurance testing also a characterisation of the gears efficiency as room temperature as well as an operating period at deep temperature (-150°C) was foreseen[3].

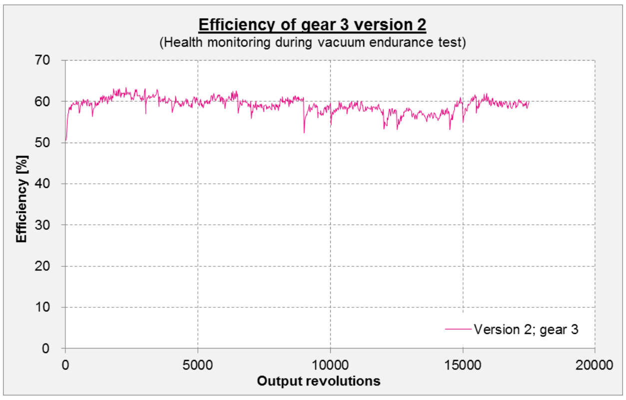

Figure 5.4-3: Efficiency course of gear 3 version 2

Table 5.4-1 shows the efficiencies for operating points between 4Nm and 12Nm output torque at an input speed between 50min^{-1} and 250min^{-1}. The efficiency was found at a level slightly above 80% being fairly insensitive to output torque and operating speed.

	Input speed [min^{-1}]			
Torque [Nm]	50	100	150	250
4	0.80	0.84	0.83	0.84
8	0.82	0.84	0.84	0.84
12	0.83	0.84	0.83	0.84

Table 5.4-1: Efficiency of dry lubricated Harmonic Drive® gear at room temperature

[3] In this case the parasitic torques for the support bearings were considered for the efficiency characterisation and for health monitoring

The course of the efficiency monitoring is shown in Figure 5.4-4. After a period of 1000 OPR at 20°C the temperature was decreased to -150°C where the gear operated for 1200 revolutions. During this period the efficiency drops to 50%. This decrease is linked to differences in the thermal expansion of the materials used within the gear, especially the ceramic balls within the bearing. This causes an increase in the preload which affects as well the efficiency. After completion of 1,200 OPR the temperature was increased back to 20°C and the endurance test was continued. The efficiency recovered to the same level as before the cold cycle but started to drop slowly afterwards until the test was prematurely stopped after 5,700OPR as the efficiency got scattered. The inspection after the test unveiled that the gear had failed.

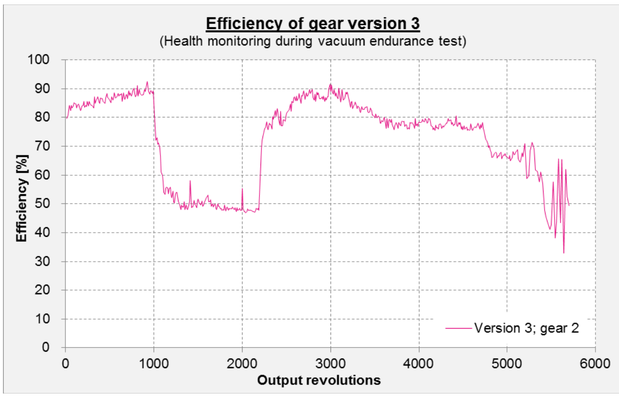

Figure 5.4-4: Efficiency course of gear version 3

5.5 Results of post-test inspection

After the vacuum endurance testing the gears were subjected to a detailed post – test inspection, which comprises a visual inspection, a characterisation and a SEM analysis. A representative example of the post-test investigation for a failed and for a successful test shall be given in the following.

As mentioned above for the initial gear versions the lifetime was limited. A typical observation after an abortive test was that the gear showed backlash. This was in most cases linked to a failure within the toothing. Figure 5.5-1 shows the result of a SEM analysis of a gear 1st CV. Wear within the toothing can clearly be identified.

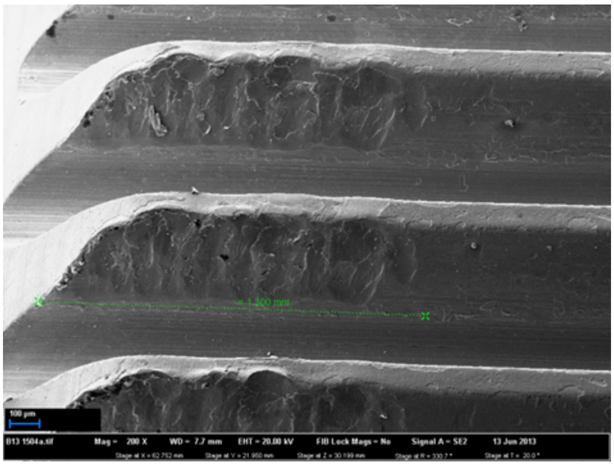

Figure 5.5-1: SEM image of the toothing of a gear of 1st CV, after failure in vacuum endurance testing.

On the contrary, final gears of version 2.2 were found in good condition at the end of the test (Figure 5.5-3). The gear characteristics remained unchanged throughout the entire operation duration. Figure 5.5-2 depicts the respective stiffness curves which are identical.

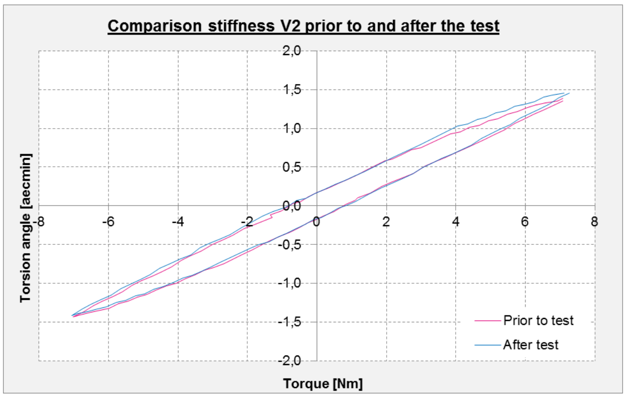

Figure 5.5-2: Stiffness curve of gear V2 prior to and after test.

The appearance of the toothing confirms the result of the stiffness measurement. The teeth are in proper condition. Detailed analysis of the contact surfaces revealed that in such cases, the reinforced MoS_2/WC coating is still present.

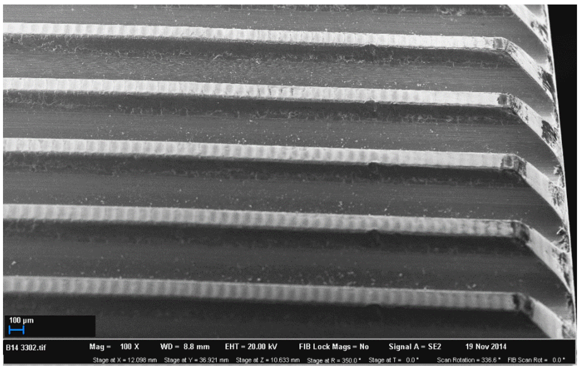

Figure 5.5-3: SEM image of the toothing of a gear version V2.2, gear did not fail during vacuum test.

6. SUMMARY

Within the project a standard Harmonic Drive® gear was step by step modified towards the needs of dry lubrication. The modifications were successively introduced to prototype gears which were subjected to vacuum testing. With the systematic approach the endurance could be increased from less than 100 revolutions at the beginning to 17,500 OPR for a prototype of a gear version 2 (ref. to Figure 6-1). 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.

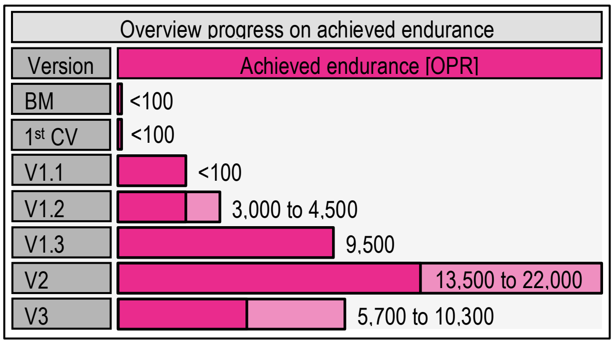

Figure 6-1: Overview on achieved endurance

Based on the gained knowledge another step forward was intended with the design of the version 3. Again the geometry was adopted and the coating configuration was modified. 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 is comparably short to those received with the version 2. Obviously, with the introduction of the last optimisations the development was exaggerated at a certain point.

7. References

1. Jansson, M., Koenen, H., Viviente, José-Luis, Tvaruzka, A., Merstallinger, A. (2013), Development of dry lubricated Harmonic Drives for Space Applications („harmLES"), 15th European Space Mechanisms and Tribology Symposium.
2. Buttery, M., Houton, K.A. (2011). ESA-ESTL-TM-0068 02-, Repeatability of friction and wear properties of Sintimid 15M / Tecasint 1391
3. Brizuela, M., Garcia-Luis, A., Onate, J.I., Garmendia, I. (2009), Tribolab: An experiment on space tribology. In–orbit data at the ISS, In Proc. 13th European Space Mechnisms and Tribology

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