TORQUE ENHANCEMENT OF DRY LUBRICATED HARMONIC® DRIVE GEARS

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1 ABSTRACT

Today Harmonic Drive® gears have become standard for various mechanisms in space applications. Providing advantages like high reduction ratio, zero backlash or high stiffness make them an ideal choice for many devices.
Anyway, nowadays technical limitations exist e. g. regarding lubrication. This accounts especially for dry lubrication where, although significant advancement has been made, load bearing capacity is very limited. Furthermore numerous applications would benefit from even higher reduction ratio than currently available, which needs downsizing of gear teeth.
The Harmades project aims to overcome both limitations by developing a gear ZirconLine-14-160 with increased load bearing capacity. By introducing a high reduction ratio to small gears, teeth with significantly decreased module are necessary. This opens options for notably increased ratios in larger gear sizes. Furthermore by introducing a nitriding process for the gear components, load bearing capability is supposed to enhance, especially for dry lubrication.

2 PROJECT GOAL

Starting in July 2016, the Harmades project aims for basic technology development that allows increasing the load bearing capability of dry lubricated Harmonic Drive® gears for space. Furthermore – by introducing a gearing with very small module – the baseline for higher ratios in one stage shall be developed. Therefore two main topics need to be considered.
This is on the one hand the downsizing of the gear geometry. Following the results in [1] and [2], by introducing a specific gear design (e. g. tooth shape and kinematic), the Harmonic Drive® gear can be optimized for dry lubrication. This development was performed introducing a gear ZirconLine-20-100. Understanding the impact of the geometric adaptations allows transfer of the optimized design to the new, smaller gear. The technical challenge is linked to the downsized toothing that has not yet been produced in such small scale.
The second topic is the load bearing capability of the gearing. It is known that the life limiting tribological contact for dry lubricated Harmonic Drive® gears is the toothing of Flexspline (FS) and Circular Spline (CS). In order to increase the wear resistance of gears in general, a common method is to harden the contact partners which is e. g. used for planetary or spur gears. In the frame of this project, a heat treatment process based on plasma nitriding shall be elaborated which can be used for Harmonic Drive® gears made of typically used materials for space. This process shall be applied to FS and CS in order to increase the hardness of the toothing. This in turn should give better support to the coating which is used for lubrication.

The development performed in the frame of this project will be based on the example of a gear ZirconLine-14-160. Selected specified performance data can be found in Tab. 1. As currently there is no gear size 14 ratio 160 existing, characteristics of an industrial gear size 14 ratio 100 are adduced as reference. Stiffness and Transmission Accuracy (TA) are supposed to be similar. Zero backlash, as one of the main features of Harmonic Drive® gears, shall remain also for the dry lubricated gear. Due to the higher ratio, No Load Starting Torque (NLST) shall be decreased by 25% compared to the industrial gear with ratio 100.
Regarding the increase of load bearing capacity, the target for transmittable output torque and achievable endurance is based on the results achieved with the gear ZirconLine-20-100 in [2]. The newly developed gear shall provide same lifetime (in output revolutions) at similar output torque. Due to the reduced gear size, therefore torque density will be increased by a factor of 2.5.

Table 1: Overview on intended gear performance

Designation	ZirconLine-14-160	
Size	14	
Ratio	160	
Dimensions		
	Length [mm]	24
	Outer diameter [mm]	50
Characteristics		
	Zero Backlash	Yes
	Min. Stiffness [Nm/rad]	3.300
	Transmission Accuracy [arcsec]	90
	No Load Starting Torque [Nmm]	16
Endurance		
	Load	4
	No. of OPR	17.500

3 DEVELOPMENT APPROACH

In order to achieve the objective of the project, the development approach is separated into four main steps as shown in the schematic depiction Fig. 1.

On gear level, the design based on the transfer of elaborated knowledge needs to be realized, taking into account the machinability of parts and tools – especially for the toothing. This will initially be performed neglecting any impact of the heat treatment on the geometry. Gear design will be verified by testing of main gear characteristics as well as achievable endurance.

A basic demand regarding the material is to develop a stable, reproducible nitriding process for the specific precipitation hardening steels. This is initially performed with simple discs providing a flat geometry.

In order to transfer the nitriding process to the gear, in a next step as well segments and complete FS and CS will be subjected to nitriding, in order to verify the process and to figure out any influence of the heat treatment on components geometry.

Finally, in the last step, the gear will be redesigned taking into account on the one hand the results of testing of the non-nitrided gears, on the other hand the impact of the heat treatment on the gears geometry.

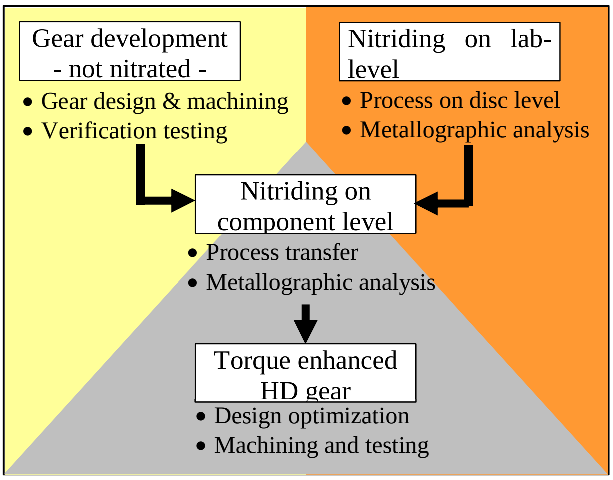

Figure 1: Schematic depiction development approach

4 DEVELOPMENT HEAT TREATMENT

4.1 On material level

A main challenge within the project is the development of an appropriate plasma nitriding process for the used materials (ref. to Tab. 2) for FS and CS. Looking on the steels, due to the needs of corrosion resistance, they contain high amount of chromium (>13%). It is known that especially steels with huge chromium content tend to form inhomogeneous nitriding layers with locally non-hardened areas as shown in Fig. 2.

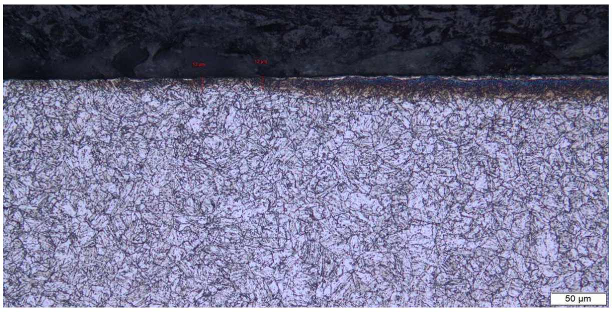

Figure 2: Inhomogeneous nitriding layer on flat sample

Referring to the plasma nitriding process, the characteristic of the nitriding layer is depending on numerous process parameters, which are for example:

- Temperature
- Duration of nitriding process
- Gas composition
- Pressure
- Voltage

The number of parameters leaves huge variety of options to vary the characteristic of the generated nitriding layer. In the frame of the project it was found that there is one main process parameter which determines the homogeneity of the nitriding layer (ref.to [5]). Choosing the correct range for the main parameter allows a variation of the further parameters without affecting the homogeneity of the layer. An example for a uniformly nitrided disc is depicted in Fig. 3.

Figure 3: Uniform nitriding layer on flat sample

4.2 On component level

Looking on the FS and the CS, the focus is set towards two main objectives which are:

- Generation of a uniform nitriding layer on the complex tooth geometry.
- Geometric changes of the gear components and their potential impact on the performance.

In order to transfer the elaborated process from disc level to FS and CS, the first step was to use segments of the gear components. Therefore parts were cut and subjected to the nitriding process whereas, based on the knowledge gained throughout testing on disc level, the process parameters were adapted. Specifically this means that the main parameter was kept within the known range, whereas the other parameters were varied to generate a nitriding layer with the demanded characteristics. The aim was to create a uniform nitriding layer over the entire tooth flank which provides high hardness without being brittle. The results of the tests performed on segments showed that it is in principle possible to create the desired uniform layer with a thickness of 17 µm to 20 µm and a hardness of more than 800 HV 0.5 on the surface. Fig. 4 depicts the microsection of a CS tooth after nitriding of the respective segment.

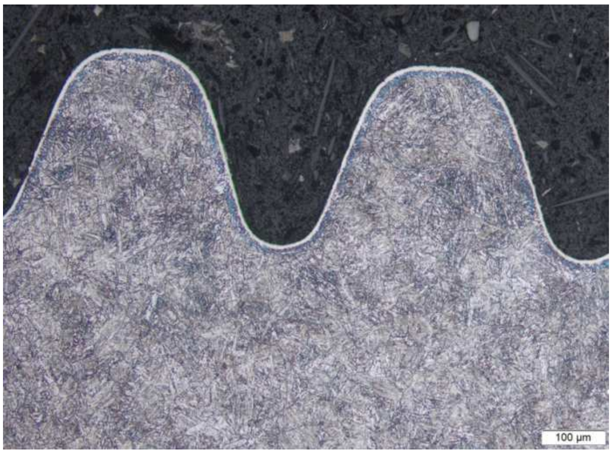

Figure 4: Microsection of Circular Spline tooth after nitriding

Having shown on segment level that the creation of a homogeneous layer over the entire tooth flank is possible in principle, the process was applied to complete gear components. Therefore 4 Flexsplines and 4 Circular Splines were subjected to an initial plasma nitriding. Fig. 5 shows an example of a Flexspline prior to nitriding with the covering device assembled and the appearance of the FS after nitriding. The typical discoloration is clearly visible.

Figure 5 left: FS prior to nitriding with covering device, right: FS after nitriding

The metallographic and geometric analysis of the nitrated components is currently ongoing. Although the expected thickness of the nitrating layer is around 20 µm only, first geometric measurements indicate a remarkable geometric change especially for the Flexspline which needs to be considered for the further gear development.

5 DEVELOPMENT HARMONIC DRIVE® GEAR

5.1 Gear design

Following the overall development approach described in chapter 3, the gear development is divided in two steps. First the design is performed without nitriding, in the second step the nitriding treatment is introduced to the components. As gear design aims for the development of a new ratio for size 14, as shown in Fig. 6, two additional sub-steps will be added on gear level.
In order to proof the feasibility of the gear in general, first prototypes will be grease lubricated to decrease the risk of tribological failure. Dry lubrication will be applied once the general functionality of the reducer is verified. The same approach is chosen for the introduction of nitriding – first nitrided prototypes will be liquid lubricated. Dry lubrication will be used in the final development step.

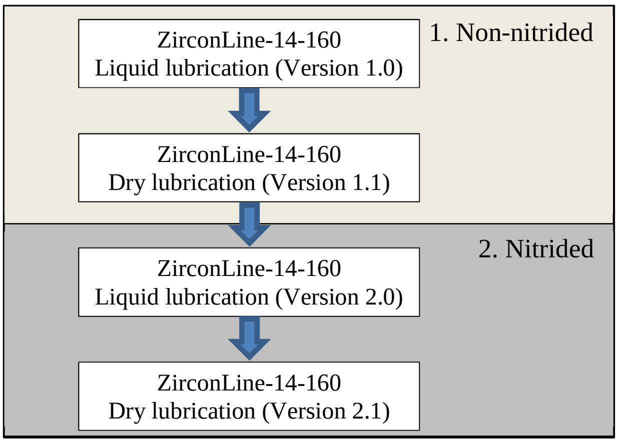

Figure 6: Development logic on gear level

As material selection for components in space is limited, most chosen materials are quasi – standard for Harmonic Drive® space gears. This accounts especially for FS and CS which is the same material as the one selected for the optimisation of the nitriding process.
The Wave Generator Bearing (WGB) is a hybrid bearing consisting of steel rings and ceramic balls. The rings are made of Cronidur®30, a high-nitrogen bearing steel which has already been used in Harmonic Drive® gears for space (ref to [4]). For the rolling elements Zirconia was selected. The main driver to choose this specific ceramic is the coefficient of thermal expansion (CTE), which is similar to steel. As the gear is supposed to operate over a wide temperature range, an impact on gear performance due to thermal expansion or shrinkage

shall be avoided therewith. As retainer material, a MoS2 containing polyimide was chosen, which was considered as potential European candidate for retainer material in dry lubricated bearings [3]. Tab. 2 presents the materials used for the different components and their CTEs.

Table 2: Materials chosen for the gear with the respective CTE (valid between 20 °C and 100 °C)

Component		Material	
		Designation	CTE [K^{-1}]
Flexspline		15-5 PH cond. H1075 AMS 5659 Type 1	$11.0*10^{-6}$
Circular Spline		17-4 PH cond. H1150 AMS 5643	$11.3*10^{-6}$
Wave Generator			
	Bearing rings	X30 Cr Mo N 15 1	$10.6*10^{-6}$
	Bearing balls	ZrO_2	$10.5*10^{-6}$
	Retainer	Tecasint® 2391	n. a.

Besides material selection, a major design challenge was the downsizing of the gear realising the optimized geometry for dry lubrication as elaborated in [2]. This accounts especially for the toothing – as a downsizing of the module of the teeth to 0.1 mm is necessary – but also to the gear kinematic.
Besides minor adaptations, the intended geometry was realized for the new gear. Contact stress and sliding path, especially within the toothing, was optimized for dry lubrication.
The principal manufacturability of gears ZirconLine-14-160 was shown by machining of the first non-nitrided and non-coated prototypes as shown in Fig. 7.

Figure 7: Prototype ZirconLine-14-160 in non-coated condition

5.2 Analysis

Before start of manufacturing and testing of the first component sets, detailed analysis of the gear was performed. This covers the contact stresses within the different contacting areas such as e. g. the toothing and the WGB for different loads, but also an estimation concerning potential overload capacity such as the buckling torque.
The contact stress was calculated using an especially developed FE-Model of a full Harmonic Drive® gear. It allows deriving the contact stresses within the toothing directly out of the model, whereas for the WGB only the contact force for each single ball is computed. Contact stress is than calculated based on the Hertzian theory in a post processing. Fig. 8 shows a typical FE-Model used for the described calculation.

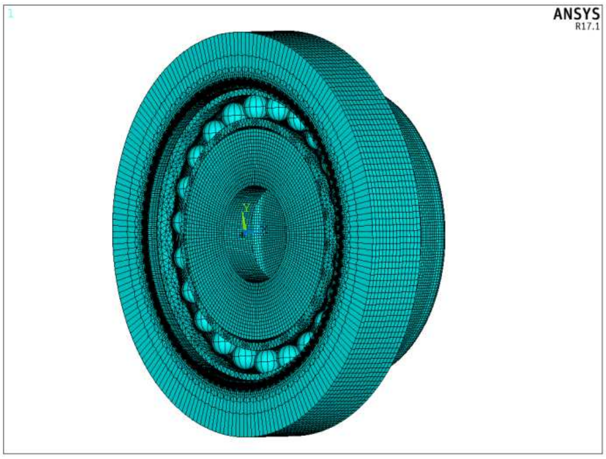

Figure 8: FE model of a full Harmonic Drive® gear

In the frame of the analysis, the maximum contact stress within the toothing and within the WGB was calculated for loads between 0 Nm and 16 Nm. Fig. 9 depicts the result of the analysis.

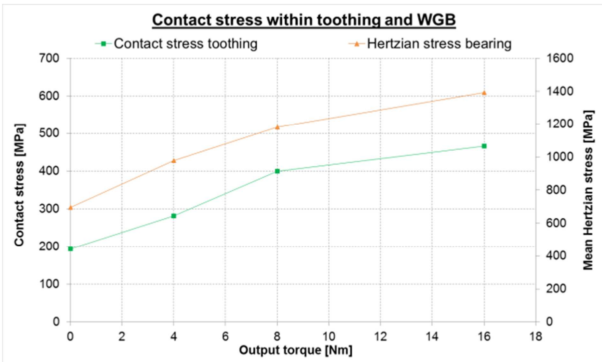

Figure 9: Stress within toothing and WGB

As expected, the contact stress increases with the applied output torque, whereas – especially when coming to higher loads – a slight degressive trend is visible. Furthermore the impact of the gear preloading, which is mandatory for the zero backlash, is clearly visible. It leads to a contact stress within the toothing of approximately 200 MPa, within the bearing the mean Hertzian stress amounts to 700 MPa, although no external load is applied to the gear. With a maximum

calculated load of 16 Nm the stress increases to approximately 450 MPa for the gearing and 1400 MPa mean Hertzian stress for the WGB respectively.
Compared to standard Harmonic Drive® gears the values especially for the low torque region are reduced due to the adopted geometry. Looking for example on the contact stress within the WGB for a standard space gear at nominal load and comparing it to the present component set a reduction of approximately 30 % in the mean Hertzian stress is achieved.
Anyway, reducing the contact stress by introduction of respective geometric adaptations causes in turn a decrease in the applicable overload torques. As an example the expected buckling torque for the newly developed gear is at a level of 60 Nm. Compared to standard space gears size 14, which provide a buckling torque of 190 Nm, this is a reduction of approximately 2/3.

6 TESTING

In the frame of the ongoing project, as mentioned in chapter 5, so far first prototypes in non-nitrided condition for fluid lubrication (gear version 1.0; ref to Fig. 6) have been produced. The initial testing of the prototypes refers to two main objectives which are:

- Characterization and basic functional testing under air
- Endurance testing under vacuum
-

For the characterization overall three prototypes were considered. A selected prototype was then used for vacuum endurance testing. The following chapters summarize the results of testing up to now.

6.1 Characterization and basic functional testing

Characterization and basic functional testing was performed under normal atmospheric condition at room temperature. For the integration of the component set, a standardized test box was used allowing installation to various test rigs at Harmonic Drive AG. Lubrication was performed with a small quantity of mineral oil (CLP 68). The gear characteristics that were assessed are:

- No Load Starting Torque (NLST)
- No Load Starting Backdriving Torque (NLBT)
- Transmission accuracy (TA)
- Stiffness

Tab. 3 shows an overview on the measured results for NLST and NLBT of the first prototypes. Based on experience, prior to manufacturing, estimation with regards to maximum values was performed. Comparing the expected maximum with the measurement shows that the prototypes are well below the expected limits.

Table 3: NLST and NLBT; estimation and measurement

	NLST [Nmm]		NLBT [Nm]	
	Mean	Max	Mean	Max
Estimation	---	16	---	2.2
ZCL-14-160	4	7	0.8	1.1

Following NLST and NLBT, the TA was assessed. As given in Tab. 1, the specified limit for the gear is fixed to 90 arcsec which is a common value for Harmonic Drive® gears of size 14. Tab. 4 depicts the measured numbers for clockwise (cw) and counterclockwise (ccw) direction which are all well below specification.

Table 4: Results of TA measurement

Direction	TA [arcsec]			
	Limit	Gear 1	Gear 2	Gear 3
cw	90	49.7	39.5	35.2
ccw		48.5	40.8	33.5

An example for stiffness curves of one gear measured with output torques of 4 Nm, 5.5 Nm and 13.5 Nm is given in Fig. 10. It can be seen that the characterized prototype provides zero backlash, whereas stiffness close to the zero crossing decreases, which is common for all three prototypes.

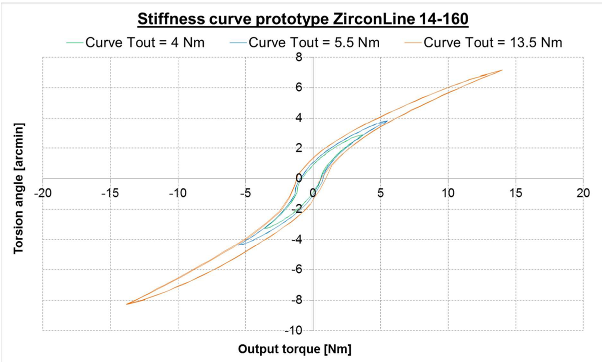

Figure 10: Stiffness curves prototype

The stiffness reduction becomes even more evident with the calculated stiffness K1 given in Tab. 5, whereas the presented value is the average of the three samples. The value K1 represents the (linearized) torsional stiffness of the component set in a torque region between 0 Nm and 2 Nm. Compared to the target value the prototypes provide stiffness below demand. Coming to the medium torque region (K2) only a slight deviation is visible, whereas at high torques values are well above the expectation.

Table 5: Result of stiffness measurement

Desig-nation	Torque region	Min. Stiffness [Nm/rad]	
		Target	Measured
K1	0 … 2 Nm	3.300	2.280
K2	2 … 6.9 Nm	6.100	5.810
K3	6.9 … 13.5 Nm	7.100	8.480

The low stiffness close to the zero crossing is caused by a geometric deviation of the FS, which occurred during manufacturing of the first prototypes. In order to save time and resources it was decided to move on with the parts, as for basic functional testing the measured deviation is in an acceptable range. The realized deviation will be corrected for the following manufacturing loops.

6.2 Vacuum endurance test

Vacuum endurance testing was performed with one prototype to verify the functionality of the gear under representative conditions.

For testing, the component set was lubricated and integrated into a vacuum suitable test box. Lubrication of the Harmonic Drive® gear was performed according to former experience gained in tests described in [4], where the focus was set toward testing of liquid lubricated gears size 20. Similar to these trials, hybrid lubrication – consisting of oil for the WGB and grease for toothing and the contact between FS and WGB – was chosen. Amounts were scaled to the smaller size, whereas Braycote® 601 EF and Fomblin® Z25 were selected as lubricant. The applied quantities are given in Tab. 6.

Table 6: Lubrication for vacuum endurance testing

Tribological contact	Lubricant	Amount [mg]
WGB races	Fomblin® Z25	62
WGB outer diameter	Braycote® 601 EF	27
FS inner diameter	Braycote® 601 EF	120
FS toothing	Braycote® 601 EF	182
CS toothing	Braycote® 601 EF	163

After lubrication and integration of the test gear into the test box, the prototype was characterized, whereas the values as given in chapter 6.1 were measured. Tab. 7 provides an overview on the gear characteristics prior to vacuum endurance test.

Table 7: Result pre-test characterization

Characteristic		Unit	Value
NLST		Nmm	4
NLBT		Nm	0.7
TA			
	cw	arcsec	46.6
	ccw	arcsec	47.2
Stiffness (K1)		Nm/rad	2350

The test parameters were fixed based on the requirements set especially for the load bearing capability of the final gear version. As the intention is to have similar test parameters along the entire development process, according to Tab. 1 the output torque was set to 4 Nm. As especially for dry lubrication the relative speed within the tribological contacts is fairly irrelevant, it was decided to go for accelerated testing with comparably high input speed of 300 rpm to keep the test duration acceptably short. Furthermore, as testing of the first prototype aims only to proof the functionality of the gear in general, temperature was set to room temperature. Test parameters are summarized in the following:

- Output torque: 4 Nm
- Input speed: 300 min^{-1}
- Temperature: 22 °C
- Vacuum level: <10^{-6} mbar
- Duration: 100.000 OPR

Vacuum endurance testing itself is performed at AAC using a rig especially developed for Harmonic Drive® gear testing. The rig has standardized interfaces allowing the integration of vacuum suitable test boxes. Furthermore, for the purpose of health monitoring, various gear characteristics can be assessed which are:

- Running torque / efficiency (continuously)
- TA, stiffness (after distinct intervals)

Fig. 11 depicts the course of the running torque of the gear at a load of 4 Nm from the beginning of the test until completion of 106.000 output revolutions. Additionally the course of the torsion angle, which is assessed during stiffness measurement, is presented.

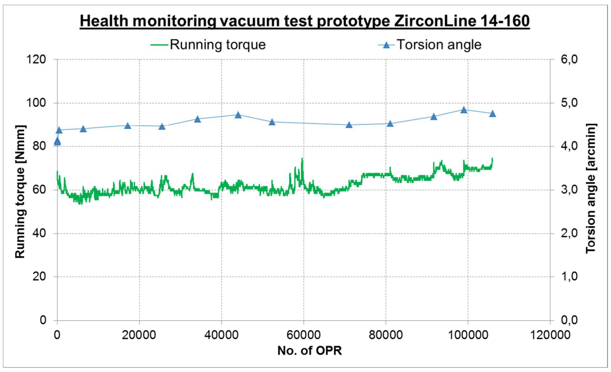

Figure 11: Results health monitoring vacuum endurance test

Referring to the input torque one can see that it is at a level around 60 Nmm. The trend of the curve is fairly constant until approx. 70,000 OPR, indicating a constant efficiency of the gear. Between 70,000 OPR and 106,000 OPR a slight increase to around 70 Nmm is visible. Looking on the torsion angle, which is representative for the gear stiffness, the effect of running-in is visible. An increase of the angle, which is measured at 4.5 Nm output torque, from 4.1 arcmin at start of test to 4.4 arcmin after 500 OPR can be ascertained. Over the following 106.000 revolutions the measured angle is only slightly increasing to 4.7 arcmin, indicating proper condition of the gear.

Fig. 12Figure 12 depicts the stiffness curves after 20, 500 and 106,000 OPR. One can see that although stiffness decreases slightly in during the test, the gear provides still zero backlash at the end of the test.

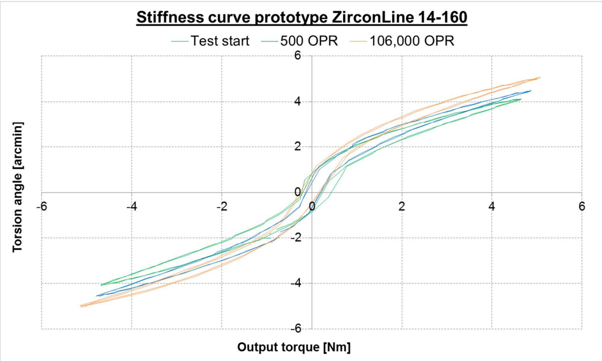

Figure 12: Stiffness curves measured during vacuum endurance test

With completion of 106,000 OPR the endurance test is finished as the targeted number of revolutions is already slightly exceeded. The characterisation of the gear will be repeated and a detailed visual inspection concerning the condition of the tribological contacts will be performed. Results will be used for further optimization of the gear geometry during the project.

7 SUMMARY AND OUTLOOK

The aim of the ongoing project is the development of a new gear ZirconLine-14-160 for dry lubrication with enhanced torque capacity. Therefore the introduction of a suitable nitriding process for material in general and specifically for the gear components is necessary. Furthermore a new gear needs to be designed accounting for the specific needs of dry lubrication. Until now, in the frame of the project promising progress could be made as well with regards to the heat treatment as concerning the gear development.

Looking on the nitriding process it was shown, that a uniform layer can be generated for the used steels. The trials on component level proved that it is in principle possible to transfer the process to the complex geometry of the gear teeth. With the optimised process a homogenous nitrating layer over the entire tooth flank can be created.

On gear level, the machinability of Harmonic Drive® gears with specific tooth profile and a module of 0.1 mm, was demonstrated. Testing of the first prototypes verified the general functionality of the new gear with respect to specific characteristics on the one hand but also concerning operation under vacuum.

Next steps within the projects will focus on the stabilization and reproducibility of the nitriding process on component level. On gear level, post-test inspection of the grease lubricated gear will be finalized. Testing of the first coated gear, which is currently in manufacturing, will follow.

8 REFERENCES

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