TRIBOLOGICAL AND BEARING PERFORMANCE OF A NEW VARIANT OF CRONIDUR X30 STEEL WITH IMPROVED RESISTANCE TO SCC

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ABSTRACT

Steels for ball bearings aim at high hardness to obtain good wear resistance and to survive high contact stresses. The trend to higher efficiency and mass reduction leads to "integrated solutions", like combining bearing with housing. Then tensile stresses appear in the bearing rings and the problem with Stress Corrosion Cracking (SCC) arises, as bearing steels are not commonly SCC-resistant and ECSS requires for all tensile loaded parts the material to be resistant against SCC.

This paper resumes the development of a heat treatment that combines SCC-resistance with proper wear resistance for selected bearing steels. It will outline the results towards SCC resistance, but will focus on the tribological performance starting from simple wear tests up to performance on bearing level: as stress critical bearing the Wave generator bearing of a Harmonic Drive ® gear was selected.

Results show that a proper heat treatment combined with high nitrogen bearing steel enables SCC-resistance and proper performance of bearing rings being subjected to tensile stresses.

1 INTRODUCTION

1.1 Objective

For ball bearings, steels were developed with a high hardness to obtain good wear resistance and to survive high contact stresses. As long as "classical bearing designs" with nominally only compressive stresses had been used, stress corrosion cracking (SCC) was no issue. However, the trend to higher efficiency and mass reduction leads to "integrated solutions", like combining bearing with housing for which tensile stresses appear in the rings and the problem with SCC compatibility arises. Former studies performed at AAC under ESA contract revealed that a threshold stress exists below which the high strength martensitic steels survive SCC-tests according to the ESA standard [1]. The obtained results showed that AISI 440C steel exhibits a stress level of only about 20% of Rp0.2, whereas for Cronidur X30 steel a stress level between 50-75% of Rp0.2 was indicated but could not be confirmed.

These findings opened the hope that a bearing steel might be "upgraded" to "high resistance against SCC", if only optimised manufacturing processes would be used. Therefore, a dedicated project was initiated to investigate the options to increase the resistance to SCC.

1.2 Study logic and definition of bread board

In a first loop, four different bearing steels and a wide set of heat treatments were selected. Specimens were machined and screened for microstructure, hardness and mechanical behaviour. Following that, Cronidur X30 was selected as most promising candidate. In order to improve its SCC-resistance, several heat treatment procedures followed by different finishing were evaluated. The down-selection of the variants of heat treatments for SCC testing was based on mechanical, tribological and microstructural analysis.

This paper will focus the tribological tests that have been performed within this project. Those started with simple Pin-on-Disc tests (air/vacuum) to assist down selection. The promising candidates were subjected to RCF-tests (Rolling Contact Fatigue) contributed by the bearing manufacturer (Cerobear). As final bread board test, a Harmonic Drive ® Gear was selected ("HD-gear"). Both rings of the Wave Generator Bearing ("WG-bearing"/ "WGB") - as one main part of the gear - are subjected to tensile stresses.

The WG-bearing rings are machined by Cerobear, with thermal treatment provided via AAC. Cerobear assembles the WG-bearing and HDSE integrated them into HD-gears of type HFUC and gear size 20. Two high load tests were run in air with HFUC-20-100 gears. Finally, a life test in thermal vacuum was run using an HFUC-20-160 gear for almost 6 months at +90°C with interim thermal cycles down to -40°C. Post-inspection was performed to validate the bearing rings to be in good condition, i.e. not to show signs of wear in the races nor degradation of its microstructure.

2 STATE OF THE ART

For application in ball bearings, steels were developed towards highest hardness to obtain good wear resistance (against abrasive particles) and being able to survive high (compressive!) contact stresses. In ball bearings Hertzian peak contact stresses up to 3 GPa are allowed for 440C assuming a hardness of 680HV [2]. And – of course – at a required pre-load, a smaller bearing enables reduction of mass thereby demanding higher contact stresses. As long as "classical bearing designs" with nominally only compressive stresses were used, SCC was not an issue. However, the trend to higher efficiency and mass reduction aims for "integrated solutions", like combining bearing with housing (flange bearings) for which ***tensile stresses appear*** and ***the problem with SCC compatibility arises***. Also a wave generator bearing (WGB) inside a Harmonic Drive® gear is subjected to tensile stresses as its rings are deflected during gear operation. The latter are typically lubricated with PFPE oil/ grease which spreads over metallic surfaces by creep effect. They are assessed as extremely stable and the amount of lubricant avoids risk of drying of the surface. Therefore, WGB surfaces are completely covered with lubricant as an environmental barrier as protection against SCC.

The ***uprising demands towards "cleanliness"*** and operation in extreme low temperature range endanger this approach, as grease lubrication often does not meet them. Then solid lubricated gears might be the solution. But here the protection by grease is not given anymore and therefore this ***solution is hindered by an appropriate SCC-resistance*** of the bearing steel for the WGB.

Prior to this project ***the existing data*** on hard bearing steels rate them as ***low SCC-resistant (Class 3)*** according to ESA ECSS [3]. Target was only to achieve high hardness in order to increase load limits in bearings. Studies by AAC under ESA contract revealed that a threshold stress exists below which they survive 30 days SCC-test: for AISI440C this level is only 20% of RP0.2 [4], [5]. For Cronidur 50-75% was indicated [6]. This opened the feasibility that ***Cronidur might become SCC-resistant when finding a proper heat treatment***. This was the ***main objective for this project "CronHard".***

Summarising all these issues raised a dilemma (being valid for all bearing steels):
High hardness is required for long life of ball bearings and seems to contradict the resistance to SCC.

As bread board, Harmonic Drive ® Gears were tested which offer ball bearings (Wave Generator bearings – depicted in *Figure 1*) whose rings are subjected to tensile stresses. The inner ring is mounted on an elliptical plug causing static stress. The outer ring is deflected twice per input revolution due to HD-gear principle causing alternating tensile stresses in the ring.

Figure 1: Wave Generator Bearing "WGB", note that the bearing is elliptical.

In general, maximum tensile stress values of WG-bearings occur at the inner ring and depend on the gear ratio. In *Table 1* estimated maximum tensile stresses within WG-bearing inner ring for gears size 20 are given.

Gear ratio	Max. Tensile stress WGB inner ring [MPa]
50	< 800
100	< 650
160	< 500

Table 1: Maximum tensile stress within WGB inner ring for gear size 20 with various ratios [7]

3 MANUFACTURING

3.1 Development of heat treatment (#AAC)

AAC had developed a specimen that enables to properly test SCC on high strength steels. Those tensile specimens were manufactured out of all selected steels by turning. After heat treatment, they were fine machined by grinding and/or fine hard turning. These specimens were used to validate the steel candidates and the heat treatments and to finally select the steel and the heat treatment for BBs, i.e. the WG-bearing rings.

3.2 Manufacturing WGB & HD

Manufacturing of WG-bearing rings (for RCF-tests and for the WGBs) followed that same general sequence: raw machining by Cerobear, heat treatment and QA by AAC, fine machining by Cerobear (hard turning). Cerobear finally assembled WG-bearings, performed standard QA and delivered one batch of WGBs to HDSE.

WGB of size 20 was selected for testing in the frame of this project in order to enable assessment of performance compared to existing data. Besides standard configuration, only the WG-rings were manufactured according to the selection of this project. The bearing balls are made of silicon nitride (Si3N4).

The manufacturing of one batch of WGBs for all HD-tests covered the raw machining (Cerobear), heat treatment to A-HT1 (AAC) followed by a metallographic check (AAC). The tested rings showed the hardness values in a range of 670HV1 (58HRC). In total, 20 inner and 20 outer WG-rings were manufactured. Ten pairs were assembled to WG-bearings and delivered to HDSE.

HDSE assembled the WG-bearings into HD-gears. Two WG-bearings were integrated in HFUC-20-100 standard industrial gears for testing in ambient (air) at high load levels and for long lifetime using industrial standard lubrication. One further WG-bearing was integrated into an HFUC-20-160 gear using space suitable materials and lubrication. Gear was then integrated in the standardized, vacuum suitable test box and subjected to vacuum endurance test. The preparation (e. g. lubrication, integration, pre-test characterisation, etc.) was performed by HDSE. The test was run in thermal vacuum at AAC.

4 EXPERIMENTAL

4.1 General material properties

The development of the heat treatment was validated initially by microstructure and hardness. With ongoing down-selection, tensile tests were added (using the same specimens as for SCC-testing). Finally, SCC-tests were performed acc. to ECSS-Q-ST-70-36 but with the specimen designed by AAC.

For testing ***of friction and wear*** on material level a High Vacuum Tribometer based on a Pin-On-Disc configuration was used (Figure 2). Test atmosphere were air and vacuum. A heating/cooling system enables testing from -100°C and +300°C. Friction forces could be resolved by +/- 0.02N. The software enables full control of the test as well as several motion types, like unidirectional or oscillating.

Pins with spherical tips were machined from selected steels with appropriate heat treatments. A load of 2N was applied, achieving a mean Hertzian contact pressure (Pm) at beginning of the test of 800MPa [8]. Further parameters were: unidirectional motion at speed 0.25 m/s, air with 50%rH, vacuum 10^{-6} mbar, room temperature. The discs were made of the same steel in same HT. Disc were grinded before friction testing to Ra~0.1µm. All samples were ultrasonically cleaned before testing. Fluid lubrication was applied by 2µL Fomblin Z25 oil. Tests were run for 100.000 revolutions.

Figure 2: High Vacuum Tribometer (Inside view). Pin and disc holding, heating system not shown.

4.2 Rolling Contact Fatigue (RCF)

The aim of rolling fatigue testing (RCF) was the investigation of the influence on the fatigue life limit of heat treatment process, resulting microstructure and hardness of the test specimen. The test specimen used for rolling fatigue life is a flat housing disc of a thrust ball bearing type 51102. Per bearing only one test specimen is used. The bearing design was adapted to ensure that the test specimen sees the higher load than its counter part and will fail first (test bearing is shown in Figure 3). The counter part is a shaft disc with curved raceway, the cage is made of PEEK carrying silicon nitride balls for testing. The counter part is also made from Cronidur X30. Standard rolling contact fatigue testing (RCF) is performed under high Hertzian stresses of 4136 MPa and full lubrication. The test conditions allow comparison of test results of different materials by life data analysis (Weibull).

Figure 3: The counter part is a shaft disc with curved raceway also from CrnidurX30, the cage is made of PEEK carrying silicon nitride balls for testing (courtesy of Cerobear).

4.3 Life test of HD-gear in ambient condition

Two HFUC-20-100 gears were tested according to HDSE standard for industrial gears. Load was applied via weights on a lever arm attached to the test rig depicted in Figure 4.

Figure 4: HD-gear endurance test rig

Compared to usual space applications, load and number of WG revolutions within test were significantly higher (82 Nm; $2.35*10^6$ output revolutions ~ $2.35*10^8$ input revolutions ~ $4.70*10^8$ WG-deflections), as general feasibility of the WG-bearings for use in HD-gears should be evaluated. The overall testing duration was about 10 weeks followed by strip-down, post-test characterization and visual inspection.

4.4 Life test of HD-gear in TVAC

The test device ("HADES") was developed with the aim to more accurately characterise HD gears in-situ (*Figure 5*). It enables to measure stiffness, transmission accuracy (TA) and Now-Load-Starting-Torque (NLST) in-situ. This means, besides the continuous monitoring of the efficiency (via input and output torque), high resolution angle resolvers inside the vacuum chamber enable to measure those three properties during a thermal vacuum test, at any time and temperature (this was extensively applied in the project HDGSA [9].

Figure 6 shows the ***setup for testing of HD gears*** inside of the HADES. On the right side, a standard gear test box is shown fitting to test devices of HDSE and AAC. Several test boxes for size 20, one for the sizes 14 and 17 are available. The final efficiency is the net efficiency of the gear (after subtracting the losses from support bearings of the test box and of all the chamber supports). This approach enables to test very efficiently a HD-gear set for performance new environmental and motion parameters.

The overall test started with preparation of the (empty) test box. Then the parasitic torques of input and output bearings in the TVAC-chamber at the relevant temperatures of the life test (RT / +90 / -40°C) were measured. The test box was then returned to HDSE, for assembly of the gear, integration to the test box and pre-test characterization. The complete test-box with gear was then sent to AAC. After integration to the TVAC-chamber, initial values were derived for TA, NLRT, stiffness and axial force in VacRT and VacHT (+90°C). The testbox was heated to +90°C, which was held throughout the endurance test. The gear was then operated at 100rpm input speed (CW). On the output side, a torque load of 4Nm was applied. The efficiency was measured continuously. For five times a thermal cycle was inserted down to -40°C and back to +90°C. Within that cycle, at -40°C / +20 and +90°C following properties were measured: TA, stiffness and axial force. This cycle was done at BOL, 20.000/40.000/60.000 and EOL (72.000). (Please refer to Figure 13 in the Annex A.)

Figure 5: 2nd Test device "HADES" for testing HDs

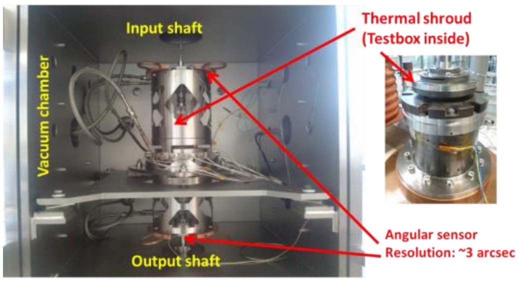

Figure 6: HADES-device for testing HDs
Insert: standard test box for HDs (by HDSE)

Finally, TA, NLRT, stiffness and axial force were measured again in VacRT. The test box was extracted and sent back to HDSE. HDSE did post-characterization, disassembly and detailed visual inspection of the relevant tribological surfaces of the WG-bearing. The gear parts were finally sent to AAC for SEM investigation of the tribological interfaces. The WG-rings were then cut and analysed for microstructure and hardness.

5 RESULTS

5.1 General properties towards SCC

The first result was to establish a Requirements Specification Document (RSD) for steels in integrated bearings in combined view by all partners. A review on bearing steels was performed and they were subjected to a trade-off. Besides material requirements, also commercial availability, European independence and market interests were considered. Following that, 4 types of steels were selected and for each of them several heat treatments (HT) were fixed as starters (Table 2).

Steel	Austenization	Tempering	Comment
Cronidur X30	1020-1050 °C	150-550°C	6 variants HT1- HT6
N360	1020-1050 °C	150-550°C	3 variants HT1-HT3
XD15 NW	1050-1070 °C	200-450°C	5 variants HT1-HT5
AISI 440C	1050-1080 °C	150-450°C	6 variants HT1-HT6

Table 2: Survey of selected candidate steels and HTs

After several loops of validating the steels with their varying heat treatments, the best performing variant became the CrondiurX30 steel with heat treatment around HT1. The main resulting properties are surveyed in Table 3. In general, the yield strength was found around 1650 MPa, being slightly lower than what can be achieved with this steel. On the other hand, in contrast to initial concerns, the hardness was found not to decrease significantly, being around 670HV/58HRC. Elongation at break ("A[%]") was found slightly to increase for the batches, except for one batch where the heat treatment failed (HT1^{SlowCooling}).

The ***Cronidur X30 with new heat treatments offers SCC-resistance up to 75% RP0.2***. From the final 3 variants of heat treatments ***only 1 of 9 specimens was broken close to the end of test,*** i.e. 1 of 9 specimens was broken after 27 days. The yield strength of Cronidur X30 after SCC-exposure was found not to decrease. Furthermore, neither corrosion nor SCC-cracks could be identified for the X30 (Figure 8). This is superior to 440C, where all specimens broke immediately after start, and reasonable corrosion signs were found (Figure 7*Figure 8*)!

Despite of the fact that Cronidur offers significant superior performance under SCC conditions than AISI440C, it has still to be classified as "Class 3–Low resistance" according to ECSS standardisation (1 specimen broken at 75%RP0.2). As mentioned above, for this type of materials thresholds exist, i.e. a tensile load levels below which they survive the SCC-test. SCC-tests on Cronidur with a new heat treatment being very similar to HT1 was run successfully at 50%RP0.2 in a further project [10]. At this level, all 3 of 3 specimens survived.

This means, that the ***Cronidur X30 can be expected to fulfil "Class 2 – Moderate" according to NASA standard MSFC-STD-3029A [11]:***

In contrast to the ECSS, the NASA-Standard [11] includes a more detailed differentiation for the Class 2 materials taking into account tests not only at 75% but also at 50% of RP02. According to NASA Standard; MSFC-STD-3029 "moderate resistance" can be rated if a material survives SCC test at a stress level of 50% of Rp0.2 (for Details please refer to Annex.).

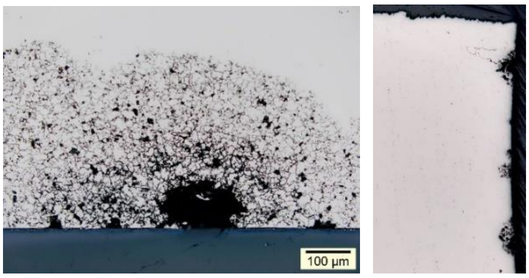

*Figure 7: **Microstructure after SCC-test of 440C at only 20% of Rp02:** control specimen with corrosion and stressed specimen with corrosion and SCC cracks.*

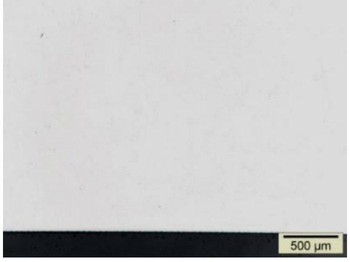

*Figure 8: **Microstructure after SCC-test of Cronidur X30 SCC at 75%RP0.2**: No corrosion and no SCC-cracks.*

5.2 Friction and wear (#AAC)

Pin-On-Disc tests were run to validate at an early stage, if a significant increase of wear rate would be caused by a reduction in hardness. Such a decrease of hardness was expected when targeting SCC-resistance.

The wear rate derived from all tests is plotted in Figure 9 (lost volume of the pin divided by the load and cumulated sliding distance). In all cases the material and its heat treatment was similar for pin and disc (as being expected in the bearing). For Cronidur (X30)-HT1, 3 parallel tests were done. Subsequently, only one test of other variants (in vacuum and air) was run. The plot shows no significant difference between the steel+HT-variants, nor between air and vacuum: the results of the single tests are within the scattering of the tests of variant X30-HT1. This leads to the conclusion that the wear rate under fluid lubrication is not significantly influenced by the heat treatment (HT). (It shall be noted that this “wear” is “wear under pure sliding”, which may be seen as a worst case overestimate for a bearing: where rolling dominates.) Moreover, the values for this “sliding” wear rate are in range of 10^{-8} mm³/Nm which is reasonable low.

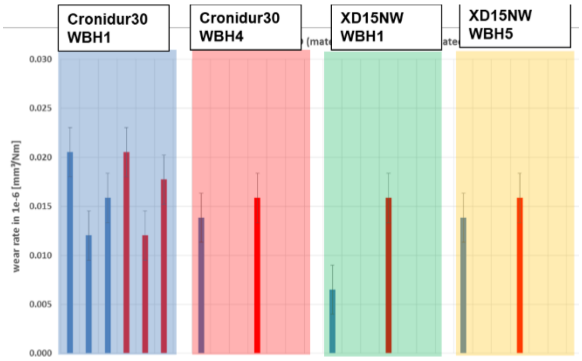

Figure 9: Wear rates not influenced by HT (statistical spread between 1 to 2.10^{-8}mm³/Nm).

Friction coefficient was for all tests in range of 0,15. Hence, no significant influence of heat treatment is identified. The value 0,15 is typical for fluid lubrication by PFPE-oil at RT.

Hence, final selection having been extracted from SCC-performance was maintained: steel CronidurX30 in heat treatment A-HT1.

5.3 Rolling Contact Fatigue (RCF) -testing

Results from first RFC-tests under high contact stresses showed a different performance for ground and hard turned test specimen. While hard turned specimen could be tested at a Hertzian stress of 4136 MPa with acceptable test times, the grinded specimen failed early. With a Hertzian stress of 3447 MPa a load situation could be identified promising for testing the grinded specimen. During analysis, it was found that during the ***heat treatment for these specimens*** quenching was not done correctly ***(HT1^{SlowCooling})***, thereby not having revealed the targeted microstructure. Hence, these results are more related to a worst case scenario rather than to the most promising one.

While the stress corrosion resistance of the proper heat treatment HT1 seems to be better than the stress corrosion resistance of other heat treatments, the maximum achievable hardness is lower than generally recommended for rolling bearings, but close to the minimum target value of 58 HRC. The reduced hardness may contribute to a reduced load capacity of the bearing. However, it can be said that the slightly lower hardness (58 HRC) can be accommodated by reducing the allowed contact stress in the bearing, e.g. from 4136MPa to 3447MPa.

5.4 HD-gear life test in ambient condition

Both HD-gears (HFUC-20-100) achieved the envisaged number of revolutions. Condition of the gears was monitored by means of change in torsion angle during interim characterization tests. Increased torsion angle represents a loss of torsional stiffness and run-in / wear condition of the gear. During the entire test duration, torsion angles showing minor changes only, indicating good condition of test specimens. Gear precision showed no change after test.

Figure 10: Raceway of outer WGB-ring of HD-Cron_1-2 after test: no wear identified

Complete post-test inspection was performed by HDSE. The lubrication was found in good state after the test. Optical microscopic inspection revealed all tribo-surfaces and interfaces in good condition (Circular Spline, Flexspline, WG-bearing outer diameter). Focusing on the WG-bearing, manual evaluation of running characteristics after tests revealed smooth running behaviour for both gears. Overall, the condition of the WGB races can be assigned as fully normal for a gear that has been subjected to endurance test under high loads. All raceways of inner rings show only minimal signs of wear, whereas numerous small indentations caused by over rolling of foreign particles can be seen. Additionally, slight formation of a boundary layer is noticeable.

Raceways of the outer rings also show only minimal signs of wear and numerous small indentations, so the condition matches with condition of inner ring raceways. Overall condition of outer ring raceways also can be assigned as normal. For both gears bearing elements are shiny and there are no indications of wear. Retainers show usual marks in the area of ball contacts.

5.5 HD-Gear life test in TVAC (#AAC)

For application testing, rings for Wave Generator Bearings (WGB) were manufactured from Cronidur, heat treated to A-HT1(developed in this project) achieving 670HV1 (58HRC) and fulfilling the manufacturing requirements for WGB. HDSE installed them into

Harmonic Drive ® gears of type HFUC-20-160. First "wear tests" were run in ambient up to 82Nm output load torque till 2.35mio output revolutions (~400mio deflections of the WG). Secondly, a similar gear was run in TVAC conditions at +90°C for 103 days (~23mio deflections). Post-investigation showed the WGBs to be in similar appearance as in previous tests using standard heat treatments. Also microstructure was found to be stable in thermal cycling and no indication was found that residual austenite is transferred into friction martensite. Referring to that, the new heat treatment (achieving less hardness of ~58HRC) does not show any indication, that risk of degradation by pitting is increased.

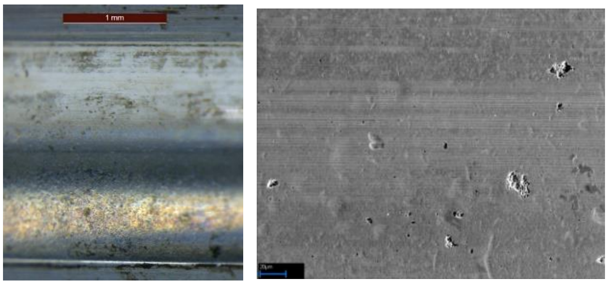

Figure 11: WGB-raceway: No wear on surface of WG-ring (optical, SEM).

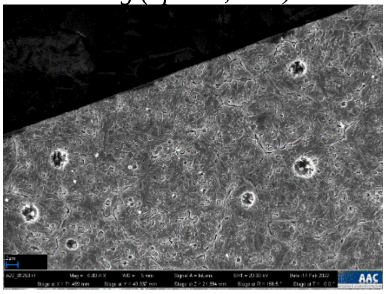

Figure 12: WGB-raceway: no cracks below raceway (SEM of cross section)

6 CONCLUSION

The high nitrogen steel Cronidur X30 together with the heat treatment A-HT1 was identified as most promising for application out of 4 types of steels, each being heat treated for 3 to 6 different procedures.

Cronidur X30 offers corrosion resistance being clearly superior to 440C.

The concern of too low hardness could be overcome, as values around 58 HRC were achieved. Yield strength of 1650 MPa is combined with improved elongation at break.

Pin-on-disc wear tests under fluid lubrication showed that the slightly reduced hardness (58HRC) did not increase wear rates significantly.

Proper performance on BB-level was confirmed by use of a Harmonic Drive ® gear. The standard WG-bearing was replaced by one made of Cronidur X30 in the new heat treatment. Two HD-tests in air and one life test for 90 days in thermal vacuum showed proper performance. ***No degradation in the subsurface zone of the races could be identified.***

The results confirm that a bearing steel may offer SCC-resistance AND sufficient hardness for bearings. For Cronidur X30 it was verified after applying a heat treatment being similar to A-HT1! The heat treatment A-HT1 on Cronidur can be extrapolated to offer on one hand ***moderate SCC-resistance (NASA) and hardness of 58HRC***.

This opens the possibility for wide ***use in tensile stressed components, like the WG-rings, integrated bearings***, etc.

The new heat treatment for Cronidur X30 is commercially available via AAC, which includes also the recommended quality inspections to assess the HT.

7 ACKNOWLEDGEMENT

The presented results were achieved within a project financed by the European Space Agency (ESA): Stress-Corrosion-Resistant Steels for Tribological Applications "CronHard" 4000115895/15/NL/LvH/hh.

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REVISION A, 2005/02/24.

9 ANNEX A:

The overall life test was run at 100 rpm input speed for the full number of revolutions that were planned.

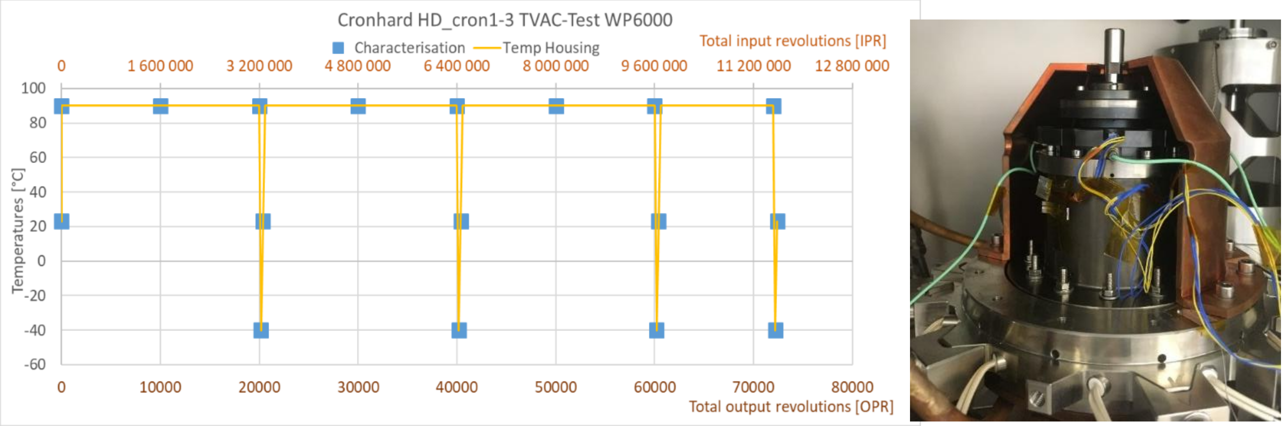

Figure 13: *LifeTest at AAC (HD_Cron 1-3), Temperature profile, performance tests at 20k/40k/60k/EOL*
Insert: Test box with gear inside installed to TVAC chamber, location of Reference ring "→"

Table 3: *Survey of results from SCC-tests for the best performing candidate: Cronidur X30 with HT1*

Heat treatment, finishing	**SCC survived**	**SCC Class**	**E (GPa)**	**RP0.2 (MPa)**	**Hardness HV/HRC**	**A (%)**
Re-HT1 (ground)	3/3	Class 1	201+/-3	1600+/-7	670 / 58.8	3 - 13
Re-HT1 (hard turned)	3/3	Class 1	204+/-3	1660 +/-27	670 / 58.8	3 - 9
HT1 (hard turned)	2/3	Class 3	207+/-7	1690 +/-14	680 / 59.2	4 - 6
HT1^{SlowCooling} (ground)(RCF)	---	---	211+/-5	1650 +/-21	670 / 58.8	~1
A-HT1 (WG-rings)	---	---	--	---	670-680 /58-59HRC	---
A-HT5 [RD-A04] (fine grinding)	3/3 @50%	NASA-Class 2	205+/-3	1622 +/-7	670 / 58.8	3-8

10 ANNEX B:

Explanation of the classification of SCC-resistance according to the standards of ECSS and NASA:

According to the ***ESA standard ECSS-Q-70-36C [2]*** there is no difference in classification of AISI440C and Cronidur30; both materials have to be graded class 3 (=low resistance to SCC) with respect to susceptibility to stress-corrosion cracking.
The main reason for this low classification of Cronidur is that at least one specimen was broken during the 30 days of stress-corrosion exposure, which is the same for “moderate” and “high”. In the following the way for the classification according to ECSS is explained.

ECSS definition [1] of “Class 2 – moderate resistance to stress-corrosion” if the following applies:

Achieved for AISI440C	Achieved for Cronidur X30	Requirement acc to ECSS-Q-70-36
NO	NO	**1**. none of the three stress-corrosion specimens fails in the thirty-day test. Any failure is disregarded if the tensile strength of the unstressed control specimen removed from test at the time of failure of the stress-corrosion specimen does not exceed the stress-corrosion test stress; and
NO	YES	**2**. the average tensile strength of the two stress-corrosion specimens after the thirty-day test is not less than 90 % of that of the unstressed control specimens; and
NO	YES	**3**. metallographic examination at ×50 magnification shows evidence of stress-corrosion in any of the three stress-corrosion specimens

In contrast to the ECSS, ***the NASA-Standard MSFC-STD-3029 [11]*** includes a more detailed differentiation for the Class 2 materials taking into account tests not only at 75% but also at 50% of RP0.2. According to NASA-Standard “moderate resistance” can be rated, if a material survives SCC test at a stress level of 50% of Rp0.2.

Class 2 – Moderate resistance to stress-corrosion rating according to NASA standard [11]:

Achieved for AISI440C	Achieved for Cronidur X30	Requirement acc to NASA MSFC-STD-3029 [11]
NO	YES	Chapter; 5.2.1.2 “Table II Requirements. Alloys, tempers, and weldments in Table II are considered **moderately resistant to stress corrosion cracking in 3.5-percent NaCl alternate immersion or 5-percent salt spray. An alloy or weldment is added to this table if no stress corrosion failures occur on specimens stressed to 50-percent of the yield strength within 30 days of exposure**.”
NO (CronidurX30 shows higher SCC resistance)	YES (no comparable alloy with higher SCC resistance)	Chapter 5.3.1.2; Table II Alloys. Alloys, tempers, and weldments that are **moderately resistant to stress corrosion can be considered for use only for cases where a suitable alloy with high resistance to stress corrosion cracking cannot be found.** NASA approval is required before using any alloy or weldment from Table II.