STAINLESS STEEL XD15NW CHARACTERIZATION FOR THE USE OF BALL BEARINGS IN THE SPACE ENVIRONMENT

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INTRODUCTION

The use of ball bearings in the space industry is commonplace, with broad range of applications from the most precise pointing mechanism to single shot device, through performance demanding reaction wheels.

Space environments might have some major consequences on the design of ball bearings. Ground environments are eligible to stress corrosion under constraint and the common limit admitted for high performance stainless steel (for ball bearings) is around 10% of the elastic limit. Moreover, space missions tend to last longer and longer, so there is also a need to increase lifetime for space mechanisms. Ball bearings are often a limiting fact in terms of lifetime and a way to improve this aspect might be to use different materials with a better behavior in terms of lifetime and with characteristics which can fulfil the needs for ball bearings applications.

X40CrMoVN16-2 (XD15NW), processed by Aubert & Duval has been used for more than 15 years in non-space applications and has shown interesting behaviors in terms of lifetime and promising results regarding the stress corrosion under constraint [1]. A study has been engaged to compare the mechanical performances between XD15NW and X105CrMo17 (440C) which is a common stainless steel used in space applications. The aim is to establish that XD15NW has a similar or better behavior as the 440C. Therefore, several test campaigns have been performed in order to compare these two materials with specific heat treatments on different aspects: metallographic characterization, hardness, admissible hertz pressure, thermal expansion and lifetime. Another test campaign has been performed only on XD15NW regarding the stress corrosion under constraint.

METALLOGRAPHIC CHARACTERIZATION

The aim of this chapter is to check that the XD15NW with ADR's specific heat treatment is compatible with usual criteria encountered in space applications and to compare these characteristics with 440C's. The tests have been performed according to ASTM standards and regarding the following criteria: Macroetch, Microetch, Average Grain Size and the distribution and carbide sizes.

Macroetch

The tests have been performed on 3 samples following the ASTM. There are four kinds of macro segregation: freckles, white spots, radial segregation and ring pattern. Each of these segregations presents 5 levels of severity according to the norm.

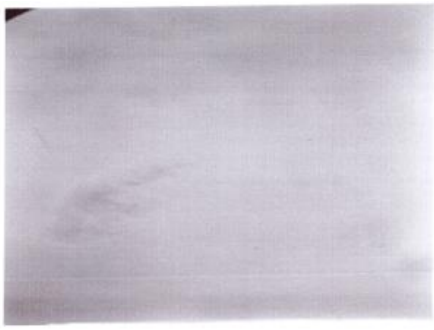

Figure 1: Macroetch observation area with optical microscope focus 100

The results are presented in table 1. On this aspect, the XD15NW is compatible with space application requirements.

Table 1: Macroetch results

Class	Severity (A=best, E=worst)
Freckles	A
White Spots	A
Radial Segregation	A
Ring Pattern	A

Microetch

In this section, the observation are made to quantify inclusions within the material, 6 samples have been examined. Four kinds of inclusion can be encountered: sulfide, alumina, silicate and globular oxides.

Figure 2: Microetch observation area with optical microscope focus 1000

Results are shown in table 2. On that second aspect, XD15NW is better than the admitted standards.

Table 2: Microetch results

A: Sulfide		B: Alumina		C: Silicate		D: Oxide	
Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick
0	0	1	0	0.5	0	1	1

Carbides size and distribution

As for other aspects, the tests have been performed according the ASTM. Tests have been performed on 3 samples. Carbides repartition is homogenous, without alignments and clusters. Maximum isolated carbides length is 35µm despite it is only 25µm for clustered ones.

Figure 3: Carbides observation area with optical microscope focus 1000

The observed parameters are within the recommendations for space applications.

Grain Size

As a noticeable difference between 440C and XD15NW is expected on this criterion, it has been examined following two methods: ASTM and EBSD analysis. The tests have been performed on 3 samples (and on both material).

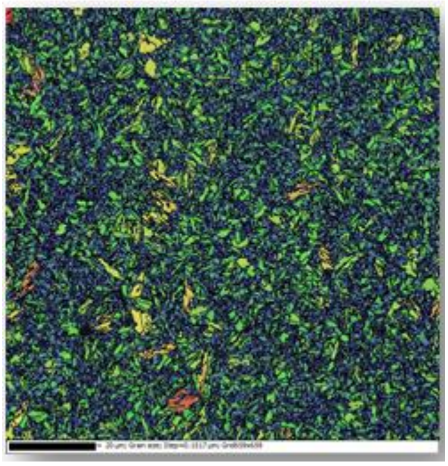

Figure 4: EBSD analysis on XD15NW

Results show that XD15NW has smaller grain size than 440C and is way above the standard admitted.

Table 3: Grain size results (*)

	XD15NW	Z100CD17
ASTM Size	11	9.5
ASTM Size	9	8

(*): higher ASTM size number corresponds to smaller grain size

Additional EBSD analysis has been performed in order to quantify the phases in both materials. And they are some disparities between both materials.

Table 4: Phase analysis

	XD15NW	Z100CD17
Martensite	91.4 %	65 %
M_7C_3	0.2 %	2 %
$M_{23}C_6$	8.4 %	33 %
Martensite Size	0.8 µm ± 0.5	1.2 µm ± 0.6

According to EBSD analysis, XD15NW has less precipitate than 440C. The martensite size in both materials confirms the observation made to determine the ASTM size of both materials.

XD15NW is compatible with these aspects of the ASTM and is eligible for space applications. XD15NW is similar to 440C in all aspects except grain size where it has smaller grain size. Smaller grain size should lead to a better lifetime and lower crack risks. Moreover, both materials with the associated process are non-oriented.

HARDNESS & HERTZ PRESSURE

The previous results are encouraging regarding the use of XD15NW for space applications but aren't sufficient for bearing applications. Several tests have been led to ensure the compatibility of this material.

Bearings theory is applicable when material presents a hardness better than 58 HRC. The hardness of a material is heavily linked to his heat treatment. The samples used to estimate the hardness have been performed on samples which have been heat treated following's one of ADR's heat treatment. Hardness tests have been measured in Vickers and then converted in Rockwell via a conversion table. The results show that the hardness of XD15NW with this heat treatment is superior to 59 HRC (5 samples).

Another major criterion for bearings application is the maximum Hertz pressure admissible. In order to estimate this limitation, a specific test method has been realized (no standard available). The idea is to apply different loads on samples and to measure the plasticizing. The maximum plastic deformation admitted is equal to 1/10000 of the ball diameter used to realize the tests. Results are presented in figure 5.

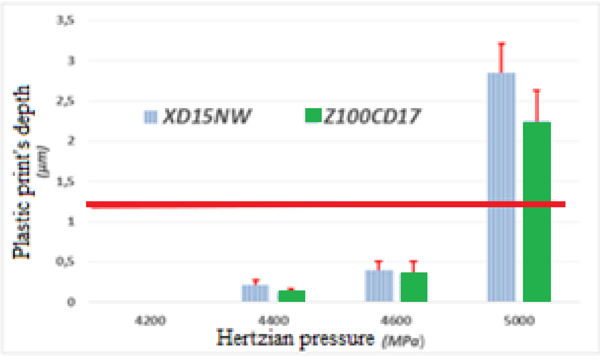

Figure 5: Plastic print's depth depending on Hertzian pressure

The behavior of both materials regarding this criterion is similar.

COEFFICIENT OF THERMAL EXPANSION (CTE)

The measurements have been realized by TMA under helium atmosphere from -55°C to 95°C. Three samples have been realized (with ADR's heat treatment) and three measurements have been realized on each.

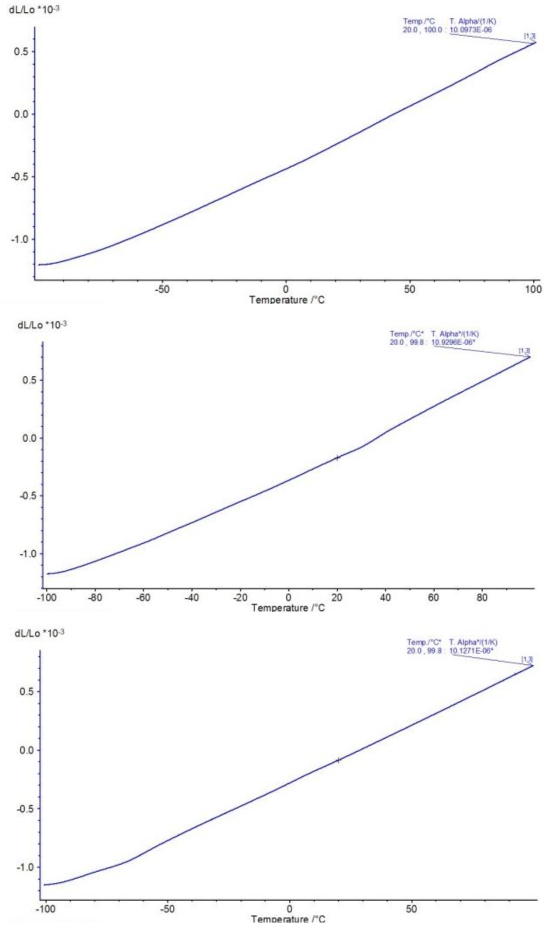

Figure 6: Expansion depending on temperature

The behavior is linear and no transition could be observed. XD15NW with this heat treatment presents a CTE of 9.91 µm/m/K.

Table 5: Steel grades thermal expansion

		Range	CTE (µm/m/K)
XD15NW	ADR Heat Treatment	+20 to +100°C	10.4 ± 0.38
XD15NW	Annealed	+20 to +100°C	10.4
440C	Annealed	+20 to +100°C	10.2

The heat treatment has a minor effect on the thermal expansion coefficient.

LIFETEST

The objective here was to compare the relative lifetime of bearings in both materials. Boundary lubrication regime was chosen for this evaluation since it is a common running condition for long life / low speed mechanisms like scan mechanisms. Boundary lubrication is known to be favorable for surface distress so it is appropriate conditions to evaluate the materials strength.

In order to accelerate the degradation, a high preload (1750MPa) was selected.

The running speed was also increased: 70rpm for a 1st stage of 15millions rev, than 150rpm until 50millions revolutions. In order to stay in a boundary lubrication regime, the temperature was increased to keep a theoretical Tallian number $\Lambda \leq 0.8$.

The setup is:

- 4 pair of bearings with same geometry mounted on separated axes
  - 2 sets with 440C rings
  - 2 sets with XD15NW rings
- Same lubrication : grease MAPLUB SH 051A + cages impregnated with oil Nye Synthetic 2001a
- Same preload : 1750MPa (applied via hard preload)
- Vacuum level $<10^{-6}$ mbar

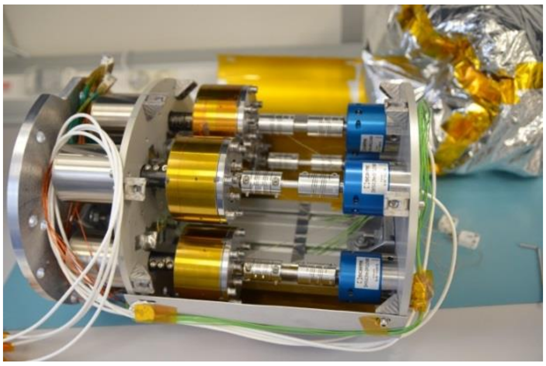

Figure 7: test bench during integration

Test bench is composed of 4 separated drive shafts, each of one including the tested bearing, a driving motor and a torquemeter. A thermal control with heaters, thermistances, MLI is also implemented.

Friction torque is continuously recording during the test, as well as environmental conditions (temperature, pressure, speed).

The evolution of the mean torque during the 2 test phases is reported on the figure 8. During phase 1, one can see an increase then stabilization of friction torque on both bearings. This seems to start later for XD15NW sets than for 440C ones. After the complete test, no failure was noticed regarding the mean torque criteria.

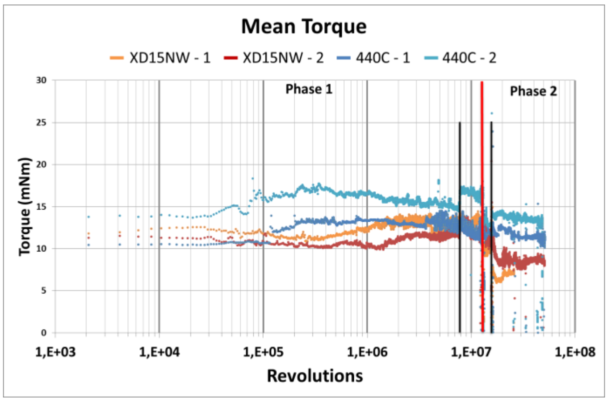

Figure 8: mean torque evolution

The evolution of mean torque represents the power needed to drive a bearing (related to motorization margin). But for high accuracy mechanisms, the torque noise depending on its frequency and level can impair the control loop performance.

A frequency analysis has been done on torque measurements. The frequencies related to ball bearing harmonics were isolated and monitored over time. These harmonics are defined by the known ball bearing geometry. They represent defect in the contact between tracks and balls. Table below gives the value of these harmonics for the selected ball-bearings.

Table 6: ball bearings harmonics

contact	Harmonics
Balls	11.3
Outer track	11.9
Inner track	14.1

Multiples of these harmonics were also observed since the torque defect is not a pure sine at the harmonic frequency. So in the frequency domain, its energy is spread on multiples of the base frequency. Du to torquemeter bandwidth limitation, only the first 3 multiples have been monitored.

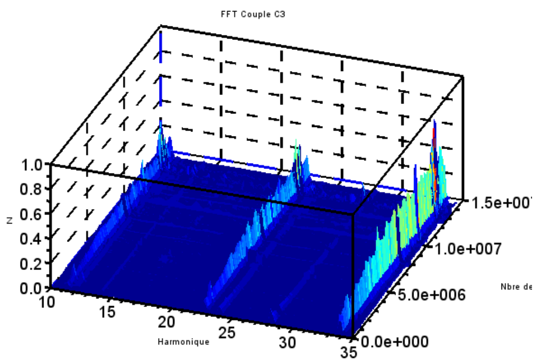

Figure 9: evolution of torque harmonics over time

During the beginning of lifetest, the noise level on each harmonic increased. But then it kept stable for the remaining part of the test. The behavior of the 4 sets was similar.

Periodically, the test was stopped to run a torque vs speed measurement. This was done to allow monitoring the viscous component of the friction torque.

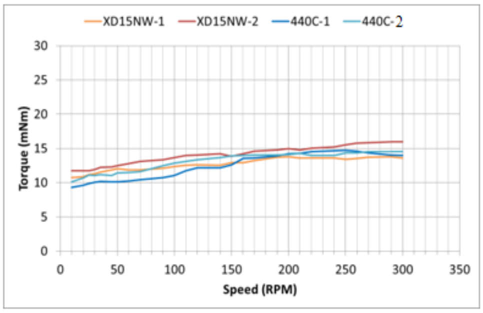

Figure 9 : Torque vs Speed measurement @test temperature

Figure 9 illustrates this measurement at the early stage of the lifetest. It has been difficult to define a viscous coefficient from these measurements since the repeatability was not stable enough. But there was a clear tendency that the viscous effect significantly decreased during phase 2 on the XD15NW sets.

The campaign has been interrupted after the bearings made 50E6 revolutions. For the final torque characterization, measurements were hardly showing sign of viscous effect, but no significant degradation of resistive torque was detected.

Figure 9: Bearings before disassembly

During the disassembly, it looked like 440C bearings had a different appearance than XD15NW ones. In fact, the XD15NW sets appeared “drier” than 440C sets. The lubricant was still present in both ones but in less quantity in the XD15NW ones. This observation correlates the torque evolution observed during the lifetest.

Optical and SEM inspections were carried out on the contact surfaces. As expected due to the very aggressive test conditions, surface tracks of bearings of both grades present some fatigue signs. However the overall wear level remains quite low on both samples, with a low amount of wear particles, despite the bad lubrication conditions

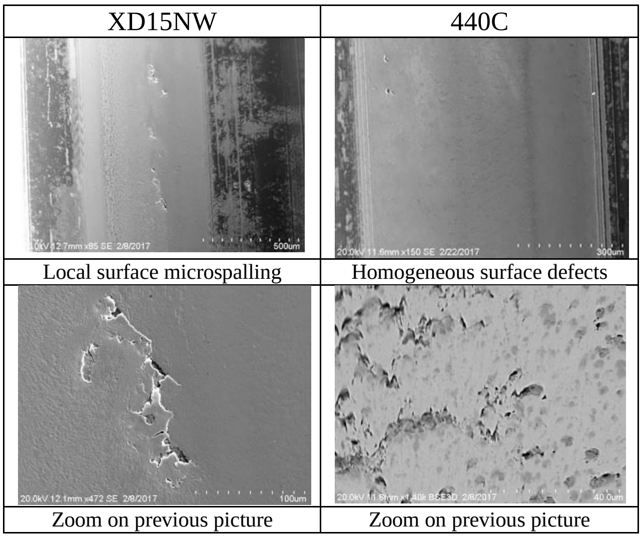

Figure 10: Post-test SEM inspection on XD15NW and 440C rings

The Figure 10 shows the differences of the surface finish of the ball-bearing for the XD15**NW** and 440C inner rings. The microspalling on track surface appears to be more important for XD15NW than 440C. This might depend on the behavior of the material itself, or a difference in lubrication condition.

In order to better understand the different lubricant behavior, some FTIR analysis has been proceeded. The idea is to check if any lubricant has been deteriorated because it could explain a bigger consumption of lubricants.

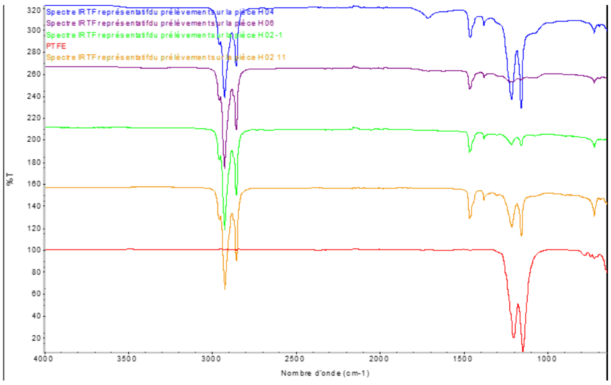

Figure 12: FTIR analysis

Figure 12 illustrates the FTIR spectrum for: PTFE (red), base lubricants (yellow and green), 440C bearing (purple) and XD15NW bearing (blue).

It can be seen that the lubricant in a bearing sets with XD15NW rings has been modified, the peak at 1710 cm^{-1} is attributed to a C=O bond (blue curve).

The peak amplitude for PTFE is changing but that is imputed to the non-homogenous repartition of PTFE in the grease samples.

Investigations are still in progress regarding surface fatigue signs and lubricant behavior.

STRESS CRACKING CORROSION (SCC)

The tested material XD15NW is a martensitic steel meeting the most ambitious requirements in terms of strength, hardness, wear resistance and also exhibiting good corrosion resistance comparable with other materials of this category (440C). However, a balance exists between superior mechanical properties on the one hand and good corrosion resistance on the other. Therefore, AAC-research has been commissioned by ESA to perform SCC-threshold testing on this material, in order to determine the maximum tensile load where this material exhibits satisfactory resistance to stress-corrosion cracking.

Figure 13: SCC probes

The tests were carried out in accordance to the standard ECSS-Q-70-37C over a period of 30 days at stress levels of 45 %(batch 1, 791 MPa), 30 % (batch 2, 527 MPa), 15 % (batch 3 and batch 4, 264 MPa) and 20 % (batch 5, 352 MPa) of the yield strength $R_{p0.2}$ in axial direction.

As already mentioned in chapter 2 three parallel specimens of each batch of the ADR- XD15NW specimens were installed in the load trains of the SCC-facility and the hydraulic pressure slowly increased aiming to the appropriate stress level of 45, 30, 20 or 15 % of $Rp_{0.2}$.

The mechanical load was maintained by connecting 3 testing rigs for each batch to a separate hydraulic pressure regulator. SCC-specimens as well as unstressed controls were immersed in 3.5 % NaCl solution for ten minutes and dried for 50 minutes which procedure was repeated over a period of 30 days. The test environment was maintained by air-conditioning at a temperature of 23 ± 2°C and a relative humidity between 40 and 50 %.

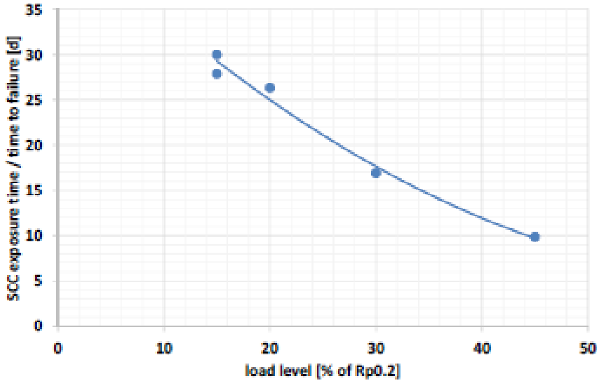

Figure 14: SCC exposure time VS load level

Results can be summarized as follows;

- The initial tensile tests, hardness measurements as well as the microstructural analysis of the material tested provided data which according to XD15NW data sheet may comply with a thermal treatment for an optimized hardness and a high corrosion resistance with austenitization at 1050°C and annealing at 180°C/1x. However, a very low amount of residual austenite found in the material refers rather to a thermal treatment in the secondary aging area which is optimized for a high working temperatures, high hardness and moderate corrosion resistance than to a thermal treatment devised for a high corrosion resistance.

- XD15NW steel tested failed the SCC tests at the stress levels of 45%, 30%, 20% and one of the two tests at the stress level of 15% of Rp0.2 showing a high susceptibility to intergranular corrosion and also to stress corrosion cracking. An investigation of the grain structure confirmed an unusually high susceptibility of the prior austenitic grain boundaries to intergranular corrosion which has been observed for the SCC test specimens.

- The corrosion and stress-corrosion cracking resistance have been for sure strongly affected by small hollows (20 to 180 µm) found on the surface and also on the fracture surfaces of the several specimens. The hollows allowed a penetration of NaCl solution into an interior where Cl ions having a permanent contact with the material caused a severe corrosion inside the specimens.

SCC results being way under expectations, some microstructure investigation were done. An etching process has been used in order to show the prior austenitic grain boundaries. This etching process is similar to a corrosive dissolution. The prior austenitic are unusually striking despite a short etching time (see figure 15). Therefore it can be assumed that the grain boundaries in the tested XD15NW steel exhibit a high susceptibility to corrosion.

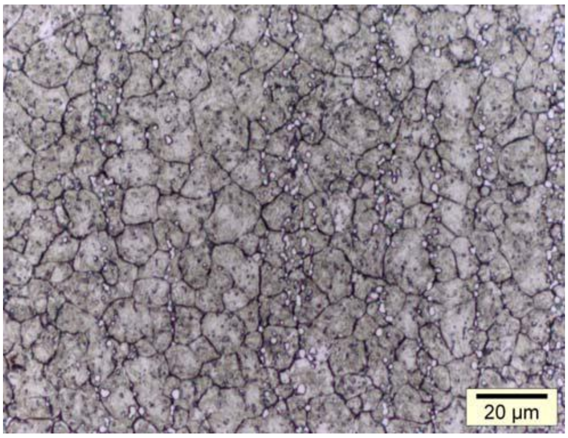

Figure 15: Microstructure of SCC specimens

After a study of the thermal treatment used for the SCC specimens, we found out that the cooling rate was too small and allowed the formation of carbides on grain boundary.

It is well known that the carbides are increasing the sensibility to corrosion. Thus, some rings were manufactured with an optimized thermal treatment in order to improve resistance to corrosion.

A new analysis of the microstructure using the same etching process was done. The figure 16 shows the differences between the two microstructures. As expected, the optimized reduce the formation of carbides and the prior austenitic grain boundaries show a better resistance to the etching process.

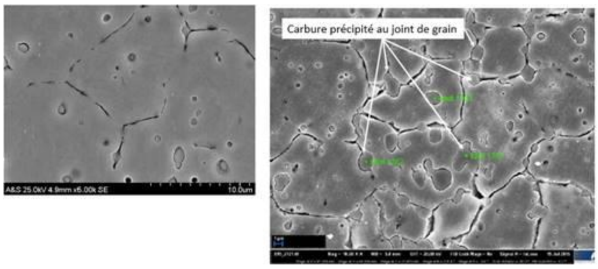

Figure 16: Differences of microstructure of XD15NW obtain (1) with the optimized thermal process and (2) SCC specimens thermal process

Because the rings are not design for SCC test, some high humidity test according the ASTM A967 was performed (practice B): specimen is subjected to 97 ± 3 % humidity at 38 ± 3 °C for a minimum of 24 h. We performed the test during 48 h and no oxidation signs (figure 17).

Figure 17: (1) Initial state of specimen, (2) state of specimen after 48 h of high humidity test.

Some high humidity tests were also performed on 440C. Two rings were performed with two different thermal treatments: the first one had no optimization of the cooling rate and the second one had an optimization in order to avoid the formation of carbides. Only 6h after the beginning of high humidity tests, both rings show some oxidation signs, and these signs increase with time (figure 18).

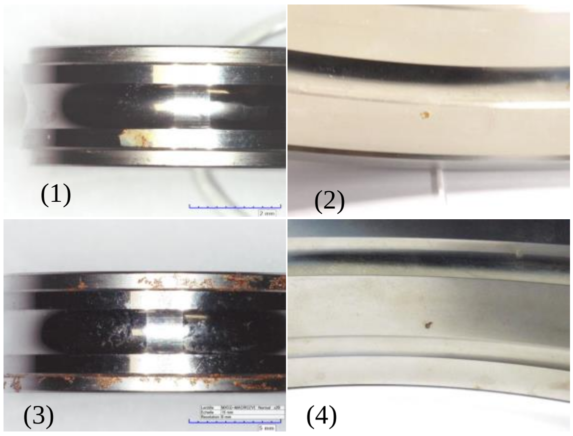

Figure 18 : (1, 3) state after 6h and 48h of test on ring with non-optimized treatment and (2,4)) state after 6h and 48h of test on ring with optimized treatment.

Therefore, we can see that the XD15NW has a higher corrosion resistance than the 440C. Moreover, results on the figure 18 shown that the reduction of carbides in the microstructure reduce the sensibility to corrosion.

It can be interesting to performed again SCC test with XD15NW specimen manufactured using optimized thermal process to quantify the gain in corrosion resistance using this material.

CONCLUSION

This activity has been done in the frame of CNES R&T program. EBSD analysis, CTE measurement, ball bearings lifetest and final inspection have been done at CNES facilities. SCC characterization has been done by ESA.

The tests results show that:

- This stainless steel grade with specific ADR heat treatment is compliant with ASTM standards regarding metallographic characteristics. XD15NW presents a more homogeneous distribution and smaller carbides than 440C.
- Hardness is > 58HRC.
- The Hertz stress limit evaluated on samples is > 4200MPa which is compliant to the ISO76 criterion for ball bearing design.
- The CTE is similar to 440C one
- A comparative lifetest evaluation between 440C and XD15NW ball bearings shows similar resistive torque behavior. Post-test inspection shows a lower residual quantity of lubricant in the XD15NW sets.
- The SCC strength is better than 440C, but still lower than expected. An optimization of the heat treatment could improve this characteristic.

XD15NW steel grade is suitable for space rated ball bearing, with better corrosion resistance than standard 440C. Lubricant consumption should be first evaluated in representative environment for new considered applications.

Further work would be needed to better understand surface fatigue phenomenon and the relation between lubricant and steel grade, and to improve the SCC strength.

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