PGM-HT AS RT/DUROÏD 5813 REPLACEMENT? LIFETIME RESULTS ON STD EARTH SCANNING SENSOR AND POLDER BEARING SHAFT

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ABSTRACT

As RT/Duroïd 5813 production ceased a few years ago, a great effort was made by space community to find a suitable alternative. Among several self-lubricating materials tested by CNES and ESA/ESTL, PGM-HT was identified by ESA/ESTL as the official alternative.

Since 2003, CNES initiated several lifetests to assess the capability of PGM-HT to replace RT/Duroïd 5813 on fully representative devices rather than on elementary test samples.

This paper presents RT/Duroïd5813 / PGM-HT materials comparison, the procurement chain used by ADR for PGM-HT cages and the results of lifetests performed on EADS/SODERN earth scanning sensor and POLDER filter wheel driving mechanism. Lifetests analyses (resistive torque evolution) added to end of life expertises underlined PGM-HT limitations concerning its capability to generate a stable PTFE/MoS_2 transfer film.

1 INTRODUCTION & CONTEXT

Self-lubricating materials are widely used for precision ball bearings in many space mechanisms when fluid lubricants cannot be used. Fluid lubricants limitations mainly concerns thermal environment or outgassing sensitivity of surrounding equipments. For self-lubricating materials, lubrication process is performed by transferring lubricants from cage to both balls and races via intermittent sliding contact at balls/cage interface all along lifetime. This process limits wear phenomenon at balls/races interfaces by regenerating lubricant coating coming from cages wear. It allows to increase mechanism's lifetime as long as this "dual transfer" is insured.

As a consequence, key parameter for choosing self-lubricating materials is mainly correlated to their capability to generate size limited wear-out particles at limited wear rate to avoid contact over lubrication. Moreover, materials selection must be performed in fully representative condition (i.e. at bearings level) and should not be limited to elementary tribometer tests using simple friction coefficient and wear mass criteria.

Among several self-lubricating materials, RT/Duroïd 5813 manufactured by Rogers Corporation has been extensively used for space bearings (for tenths of years) sometimes in conjunction with sputtered MoS_2 films applied on balls and races. RT/Duroïd 5813 production ceased a few years ago and a great effort was made by space community to find a suitable alternative. Thus, many potential replacement materials have been identified and tested since the 90s ([2], [3], [4], [6], [7]) and PGM-HT was identified by ESA/ESTL as the official candidate ([3], [4] and [7]).

The first part of this paper is dedicated to PGM-HT manufacturing, microstructure and procurement. Bearings were supplied by ADR as standard FM models with a particular care on PGM-HT cages manufacturing quality (burrs, tolerances conformity).

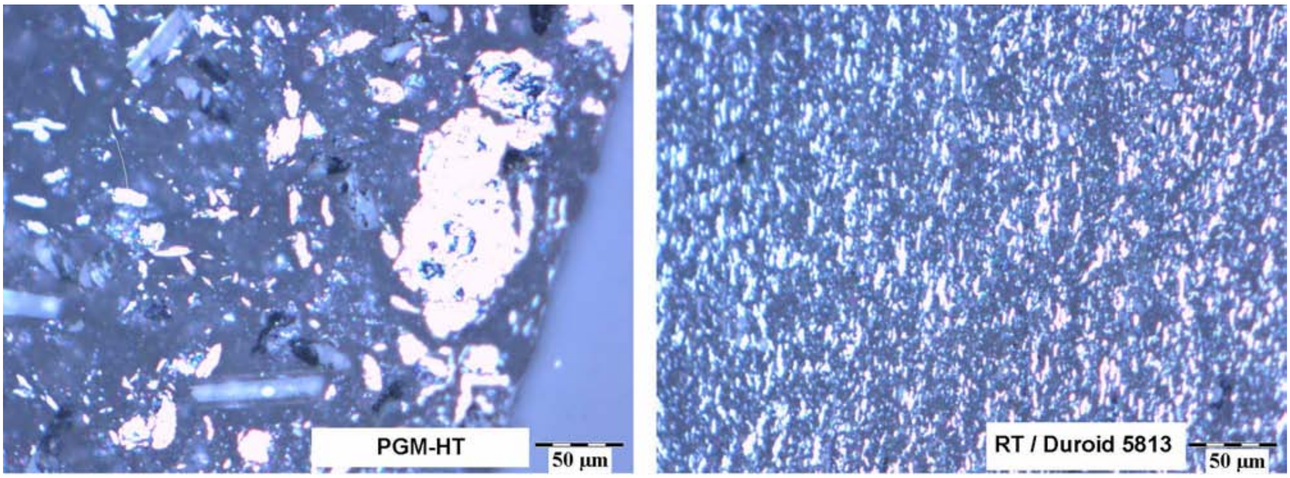

Figure 1 Comparison between RT/Duroïd 5813 and PGM-HT microstructures

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The second part is dedicated to the lifetests performed at CNES using PGM-HT caged bearings with two mechanisms already qualified with RT/Duroïd 5813 : 2 lifetests on EADS/SODERN's earth scanning sensors (STD) and 1 life test on POLDER filter wheel's bearing assembly (a second life test started in April 2009). For both mechanisms, resistive torques have been continuously registered during lifetimes and end of life bearings analyses and observations are presented.

The end of this paper is dedicated to the assessment of PGM-HT as RT/Duroïd 5813 replacement : both tribological behaviour and its consequences at bearings level are presented and compared to RT/Duroïd 5813 heritage. Lessons learned from these tests as well as additive design recommendations and particular precaution associated to PGM-HT use are also presented.

2 PGM-HT AS DUROID REPLACEMENT

2.1 Origin of PGM-HT selection

Numerous R&D activities have been achieved by CNES and ESA to find a suitable alternative to RT/Duroïd 5813 and many tests campaigns were performed for instance by CNES and ESA/ESTL on several self-lubricating materials such as Salox M, Rulon E, Rulon AMR, LUBRIFLON 907, VESPEL SP3, RULON E and PGM-HT. Among these materials SALOX-M and PGM-HT was identified as the best candidates for RT/Duroïd 5813 replacement. As for RT/Duroïd 5813, SALOX-M production ceased and PGM-HT became the logical substitute even though warnings were emitted regarding potential interactions between MoS_2 transfer film and glass fibers [4].

2.2 PGM-HT & RT/Duroïd 5813 microstructures

Although PGM-HT and RT/Duroïd 5813 compositions are very similar in ingredients and proportions, visual observations clearly indicates that PGM-HT microstructure is much coarser than RT/Duroïd 5813 one as clearly illustrated by figure 1. These differences concerns all constituents namely PTFE, glass fibers and MoS_2 particles. Thus, for PGM-HT, the MoS_2 particle size and glass fibers diameter are >100 µm and 20 µm respectively while for RT/Duroïd 5813 ones are rather < 10 µm for MoS_2 particles and 3 µm in glass fibers diameter. Tribological consequences of theses microstructures are discussed in § 5.2.

2.3 ADR procurement chain for PGM-HT

Bearings were supplied by ADR® as standard FM models with a particular care on PGM-HT cages provisioning. For each cages batch, a PGM-HT sample coming from the same material batch was provisioned. All cages were manufactured by JPM Mississipi who owns an exclusive licence for PGM-HT distribution and manufacturing [5]. ADR was not able to acquire any material batch and no European alternative was found for material provisioning. Thus, as for SALOX-M and RT/Duroïd 5813, PGM-HT is not an European product and shows poor visibility on its perennity. At this time, no strategic material batch was provisioned by ADR.

Regarding manufacturing quality both POLDER and STD bearings were controlled and selected using standard criteria associated to RT/Duroïd 5813 caged space bearings. For STD, cages were controlled by EADS/SODERN using their wide knowledge on RT/Duroïd 5813. Even though materials discrepancies presented above, no significant difference has been observed between PGM-HT and RT/Duroïd 5813 cages. According to EADS/SODERN, CNES and ADR experiences, excellent manufacture quality was commonly recognized for PGM-HT cages : no burrs or manufacturing defects were observed and all manufacturing to lerances were respected. The machining process as well as the waste proportion during manufacture are not known.

3 TESTED MECHANISMS

3.1 Test philosophy : RT/Duroïd 5813 caged mechanisms qualification Heritage

Test philosophy followed for this study consists in submitting successfully qualified mechanisms with RT/Duroïd 5813 caged bearings to new lifetests with PGM-HT cages. The aim is indeed to validate the self lubrication behavior of the new PGM-HT material on completely representative devices rather than on elementary test samples. Both mechanisms should also be different in terms of Hertz pressure under preload and of kinematics (stop/start phases) in order to get as much information as possible on PGM-HT behavior.

The selected mechanisms are an earth scanning sensor manufactured by EADS/SODERN and POLDER instrument's filter wheel bearing shaft.

3.2 EADS/SODERN Earth scanning sensor

The scanning head of STDs 15 and 16 uses rotating mirrors mounted on two annular ball bearings loaded at about $P_{Hertz} = 600$ MPa by an elastic preload. The mechanism is driven by a synchronous brushless motor. The two light ADR ball bearings have bores of Ø27 and 46 mm respectively. Both mechanism's architecture and bearings geometrical characteristics are presented on figure 2 and table 1.

This type mechanism operates in continuous rotation at 75 rpm for 15 years in orbit for GEO applications. This represents a total of about 800 million rotations.

Due to this lifespan and to other constraints, a fluid lubrication cannot be used and EADS/SODERN STDs were developed and qualified using RT/Duroïd 5813. This mechanism is widely flight proven : a total of 118 models have been launched and are successfully used in AOCS loops.

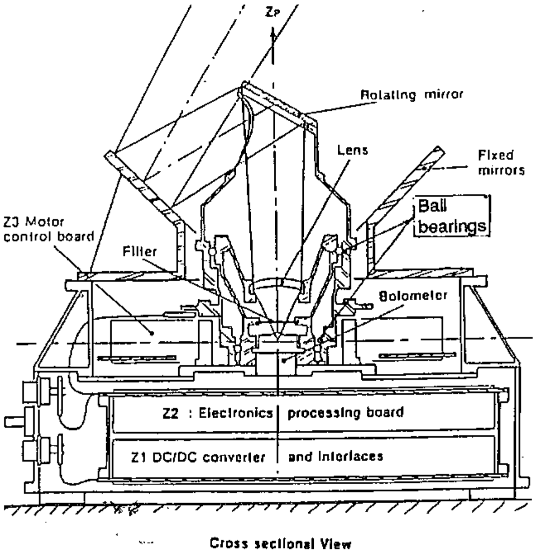

Figure 2 Cross-section of STD mechanism

Table 1 STD bearings characteristics

	Ball Bearing A	Ball bearing B
Balls diameter	3.175	3.175
Number of balls	28	18
Conformities	[0.53 ; 0.54]	
Contact angle	17.253°	17.253°
External diameter	57.15	38.1
Internal diameter	46.0375	26.987
Elastic Preload	10 N (7.10^{-3}N/µm)	
Hertzian pressure	~503 MPa	~590 MPa

3.3 POLDER Filter wheel mechanism

The second mechanism selected for PGM-HT evaluation was used to drive POLDER's filter wheel. The mechanism is made of RT/Duroïd 5813 caged duplex ball bearings assembly directly driven by a SAGEM 35 PP stepper motor. Hertz pressure due to preload is about 1100 MPa. Bearings geometrical characteristics are gathered in table 2. This mechanism is designed to achieve a total of 11 millions rotations composed by unidirectional rotations and stationary phases.

This mechanism was successfully qualified in 1996 due to high motorization margins taken during phase B : high torque instabilities were indeed observed during the lifetest performed. Since qualification, 3 mechanisms have been launched and are successfully used on PARASOL and ADEOS satellites.

Table 2 POLDER bearings characteristics

	Ball bearings pair characteristics
Balls diameter	4.762
Number of balls	2x11
Conformities	[0.54 ; 0.56]
Contact angle	~ 18.5°
External diameter	32
Internal diameter	15
Elastic Preload / PHertz	70 N (28.6 N/µm) / 1100 MPa

3.4 Test benches and test parameters

During this test campaign, STD ball bearings were mounted on a real mechanism (cf. figure 4) whereas for POLDER bearing duplex assembly is mounted in a representative mechanical assembly as for previous qualification test. Except this difference test parameters are similar for both mechanisms : the mechanisms were not submitted to vibrations, lifetests are performed under dry nitrogen and rotation speeds are 60 rpm for STD and 48 rpm including stationary phases for POLDER. In STD case, resistive torque is monitored via brushless motor current and by a static torquemeter for POLDER.

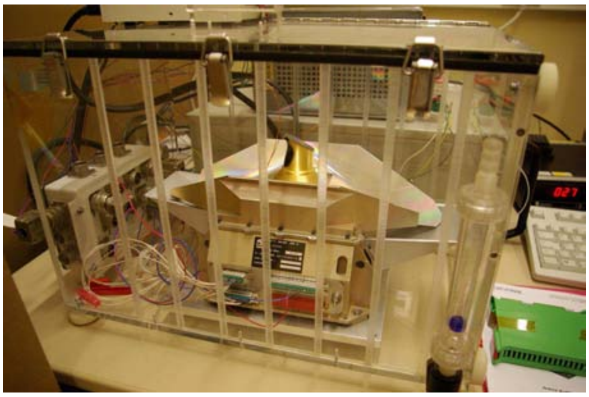

Figure 3 STD in dry nitrogen box

4 TESTS RESULTS

4.1 Previous PGM-HT caged STD15 failure [6]

From 1999 to 2003 and following the ceasing of RT/Duroïd 5813 production, a test campaign including vibrations, thermal cycling [+35°C ; +75°C] and ultra high vacuum (UHV) life test was performed by CNES and EADS/SODERN on a STD with PGM-HT lubricated bearings. This test was accelerated by a factor 8 to achieve 800 millions cycles in a reasonable time.

The lifetest was stopped after 22 millions rotations under UHV due to non acceptable increase of friction torque (multiplied by 20 during lifetest) [6]. Torque increase was attributed to excessive generation of wear particles but cages did not show significant mass loss (-0.2%) leading to the hypothesis that wear particles might originate from balls or rings (cf. figure 15).

Following this anomaly and test stop, a second lifetest began on a STD (same mechanical architecture) at room temperature and under dry nitrogen. This new test is hereby described.

4.2 STD and POLDER Resistive torques along lifetime

Resistive torque evolution of STD and POLDER mechanisms are represented on figures 6 and 7. For both mechanisms, maximum, minimum and average values (for 20 s long periods) are registered all along lifetests.

4.2.1 STD second lifetest under dry nitrogen

At this time PGM-HT caged STD accomplished about 30 millions rotations at 60 rpm. The main observations are gathered below :

- General observation : As illustrated on figure 5, the maximum, minimum and average torques are stable and no significant evolution was observed. The only artifact appeared after 12 millions rotations and is due to test interruption and test box move.

- Average torque : Typical average torque is 12mA (~ 24 gxcm including motor resistive torque). All along lifetime motor current oscillates between 11 and 15mA.

- Maximum Torque : Maximum torque reached 37 mA after ~12 millions cycles. Typical difference between maximum and average values is 18 mA which indicates that torque is quite noisy.

- Noise and FFT : During continuous torque recording (200 Hz), 2 different signal morphologies have been observed. Both morphologies are presented on figures 4 and 5. The first type consists of a classical STD signal as illustrated on figure 4. The second type is shown on figure 5 : the signal is noisier and FFT analysis ([1]) indicates that noise originates from cage localised defect interacting with bearings external ring. Such behaviour appeared by phases all along lifetime.

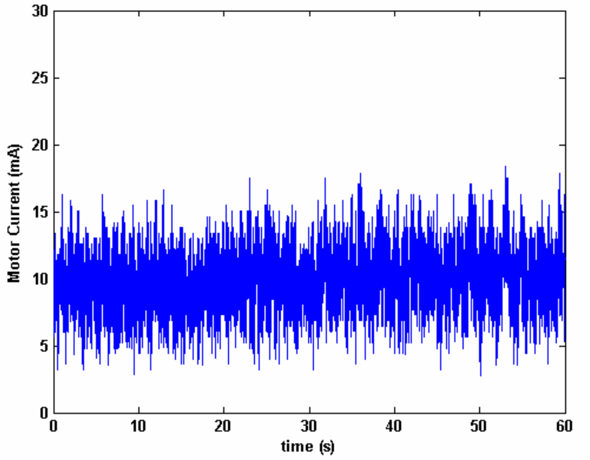

Figure 4 STD motor current during stable phases

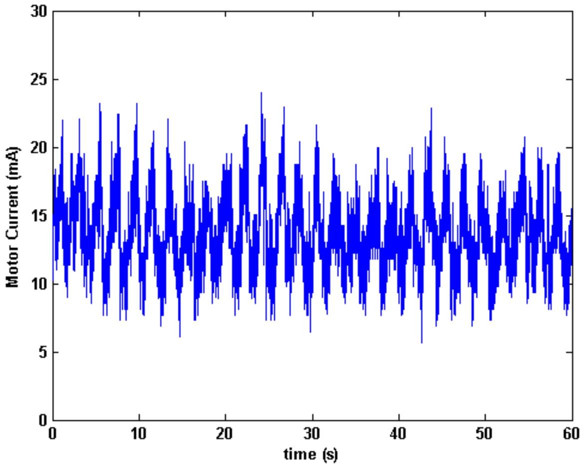

Figure 5 STD motor current during noisy phases

4.2.2 POLDER

Torque evolution during PGM-HT POLDER lifetest is summarized on figure 6. The main comments are the following :

- General observation : as illustrated on figure 8, maximum, minimum and average torque evolution is chaotic for POLDER bearings. Thus no stable phases was observed during lifetime : either the average torque (1-4 millions rotations) or the maximal (4.5 – 8 millions rotations) underwent high variations. The lifetest started with a relatively low and quiet resistive torque (~15 gxcm as illustrated on figure 9, graph on the left) which rapidly increased after 1 millions cycles. Then the torque increased until 3 millions cycles (90 gxcm average) and progressively decreased until end of life. End of life resistive torque is nevertheless quite high (35 gxcm average) compared to initial one. As for STD, FFT analyses underlined that peaks seems to be in a great part to cage defect interacting with bearings rings. Torque morphology at end of life is illustrated by figure 6.

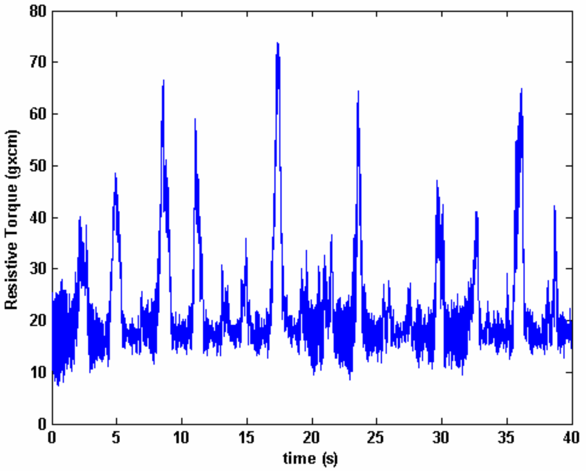

Figure 6 POLDER End of life resistive torque

- Initial torque increase : The huge increase observed after 1 million cycles corresponds to a multiplication of initial restive by a factor of 10 in a short period of time (21min). It should be noticed that a second PGM-HT caged lifetest was launched on POLDER bearings and behaves identically to the one presented on figure 6 : after a very stable phase (1,5 millions rotations at Cr < 10 gxcm), bearings resistive torque was multiplied by more than 15 to reach Cr ~ 150 gxcm. Since this increase resistive torque oscillates between stable phases at and noisy phases reaching 150 gxcm and above.

- Average torque / Max. Torque : Comparison between average and maximum torques underlines that Cr is extremely noisy ($Cr_{Max}/Cr_{Average} > 4$).

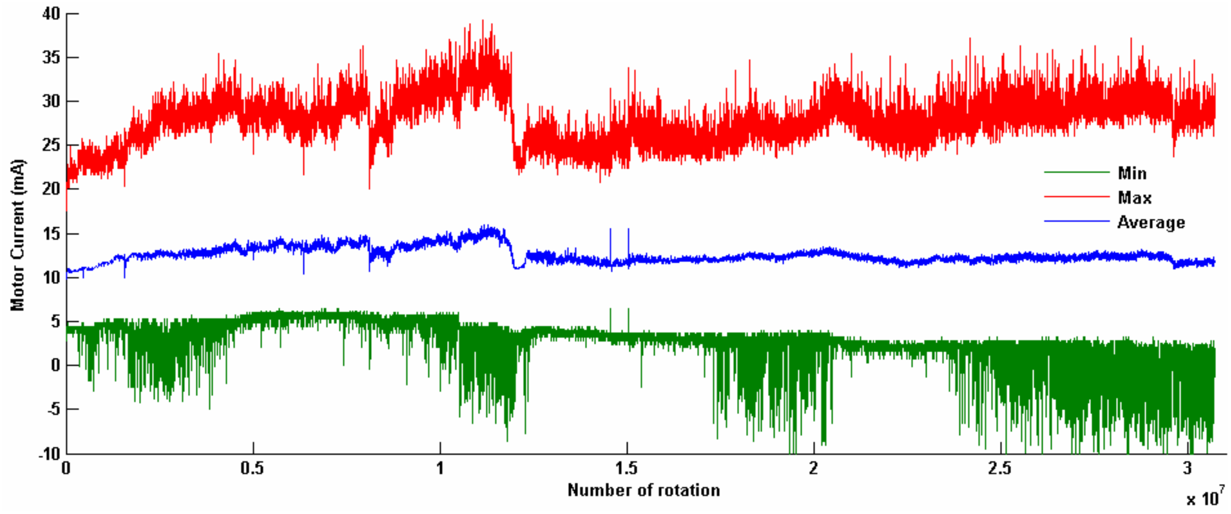

Figure 7 STD 2nd lifetest : ~ 30 millions cycles have been achieved so far (1mA = 2 gxcm).

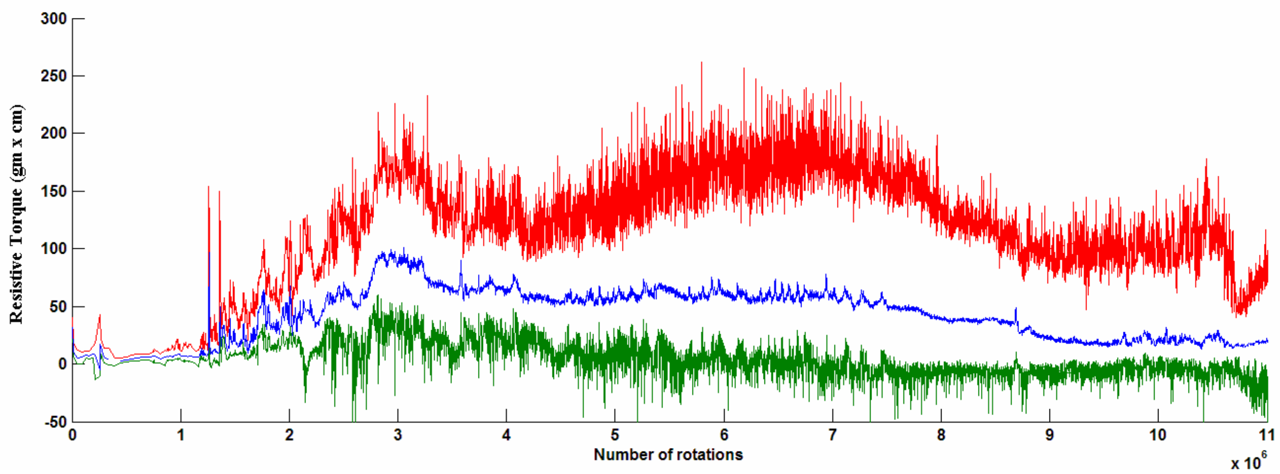

Figure 8 POLDER PGM-HT caged bearings lifetest

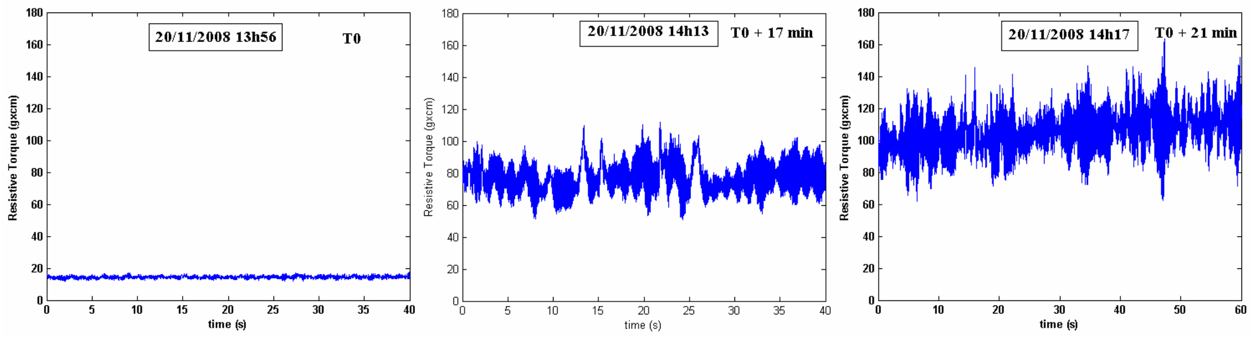

Figure 9 Torque monitoring during anomaly observed after 1 millions cycles : Cr was multiplied by 10 in 21min

4.2.3 Comparison between POLDER and STD

POLDER and STD showed significant differences. 2nd lifetest STD torque evolution illustrates a healthier behavior than POLDER one. With usual lifetest success criteria used by CNES (torque increase in addition to classical ECSS motorization margins), PGM-HT caged POLDER lifetest could be stopped after 1 millions cycles as done on first STD lifetest due to equipment limitation (motor torque). Lifetest was continued in order to assess PGM-HT behaviour for long lifetime and for comparison with RT/Duroïd 5813.

For both mechanisms, bearings sizing respects the critical Hertzian contact stress limit for PTFE/MoS_2 transfer films widely recognized by literature (P_{Hertz} < 1200 MPa, Ref. [7] and [3]). Above this pressure steel wear might occur.

Nevertheless Bearings mechanical architecture is significantly different : POLDER duplex bearing assembly preload is solid (1100MPa, 28.6 N/µm) whereas STD is elastically preloaded (~600MPa, K<0.01 N/µm, cf. figure 2). Influence of preload type and value as well as its capability to accommodate and reduce effects of wear particles trapped in the contact are questionable.

4.3 POLDER Bearings end of life inspection

In the case of first STD lifetest (failure) and POLDER bearings lifetest, PGM-HT caged bearings were dismounted and expertised by CNES and EADS/SODERN. These analyses showed similar morphologies indicating that tribological phenomena are similar.

The main observations are the following :

- **Wear particles** : Some wear particles were found inside POLDER mechanical assembly during dismounting. Regarding the total cumulated cycles (11 millions) and torque evolution during lifetest, only a small quantity of wear particles was generated. Most of wear particles were collected on bottom part of bearing assembly (on cage or rings corner and on below assembly cover). Some wear particles were also found on races edge and were pasted on balls. These wear particles clusters are made of a large number of metallic microparticles spread on races as illustrated on figure 10. Spectrometer analyses confirmed that they originate for stainless steel wear and only a small quantity of MoS_2 or PTFE were detected (cf. figure 11).

- **Races /Balls** : As observed during STD 1st lifetest expertise, a non neglectible amount of wear particles were found on races and balls as visible on figure 12, 13 and 15. A presented above, these particles are metallic ones. No MoS_2 coating or any clear transfer film was observed neither on balls nor on races. This raises the question of PGM-HT capability to release and establish a stable MoS_2 transfer film.

- **Cages :** Regarding mechanism lifetime, cages wear was very limited no significant mass loss was observed (-0,2%). This is in accordance with previous observations on wear particles quantity. Relatively low wear rate is indeed widely recognized in the literature ([3], [4], [6] and [7]). Figure 14 illustrates this comment : cage surface shows no significant wear trace. Balls/Pocket and Cages/outer rings sliding interface but PGM-HT surface morphologies as well as spectrometer analyses only shows steel wear particles.

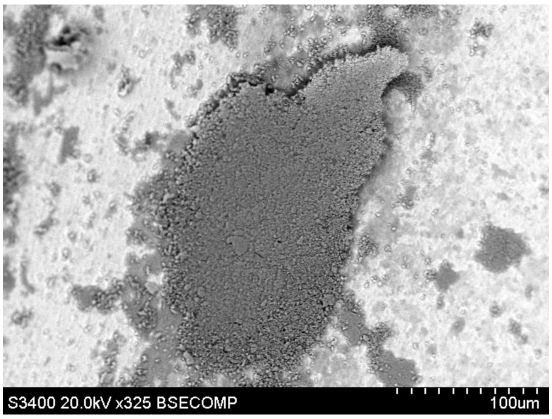

Figure 10 POLDER Steel µparticles cluster spread on race

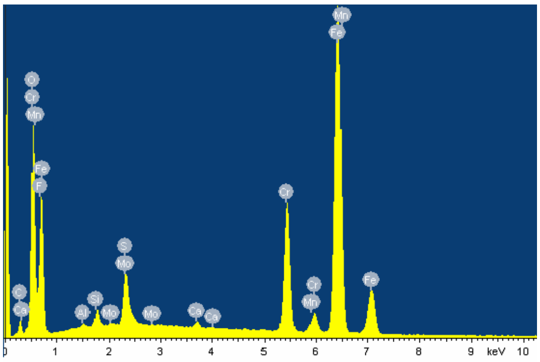

Figure 11 Spectrometer analysis of cluster (fig 10)

Figure 12 Wear particles on POLDER race

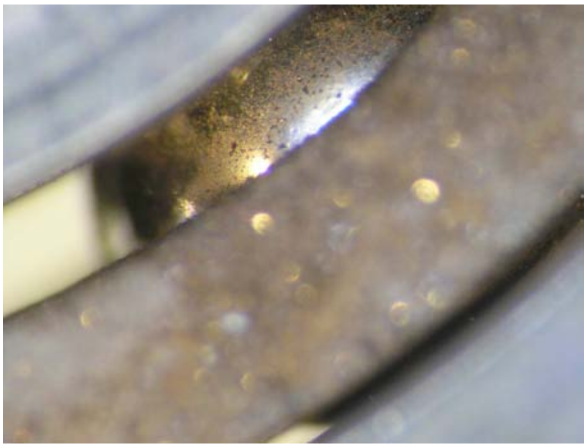

Figure 13 POLDER Wear particles on balls & cages

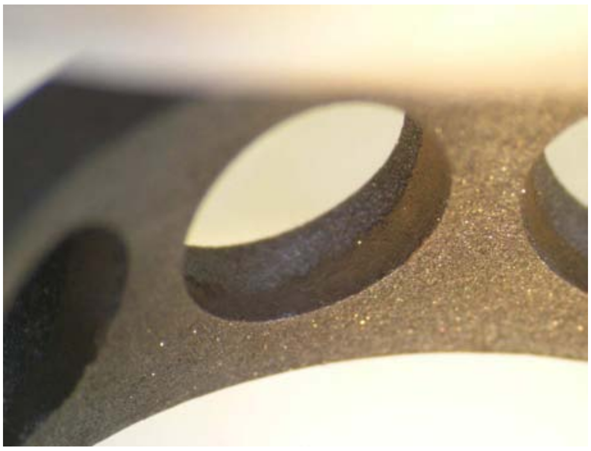

Figure 14 POLDER PGM-HT cage sliding traces

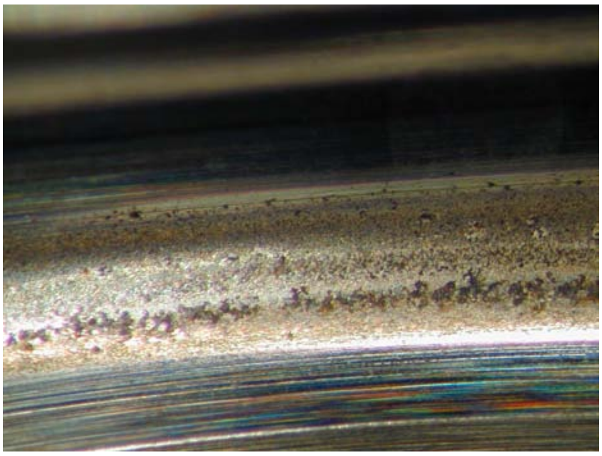

Figure 15 STD bearing PGM-HT race after UHV first life test

5 PGM-HT as RT/Duroïd 5813 replacement ?

5.1 Qualification status of POLDER & STD mechanisms

For STD earth scanning sensor, the 2nd lifetest results obtained with PGM-HT after 30 millions cycles are comparable to those obtained with the RT/Duroïd 5813. Neverthless, it should be noticed that torque's peaks as well as average torque are slightly lower for RT/Duroïd 5813 caged STD (cf. figure 16: Average current ~ 9 mA, Max current ~ 20 mA). This comparison needs to be confirmed by test's continuation.

For POLDER bearing assembly, peak torque's values reached during RT/Duroïd 5813 and PGM-HT lifetests don't show major discrepancies. Nevertheless, average torque evolutions and torque noises are significantly different: the quick and sustainable average torque increases (global deviation and instabilities on average torque) observed for PGM-HT appears critical compared to classical furtive increases observed on RT/Duroïd 5813 caged bearings (due to cages wear particle release and removal from balls/races contact).

In conclusion, whether on STD or POLDER tests, despite their different structures, RT/Duroïd 5813 and PGM-HT present relatively similar peak values at bearings level. Nevertheless, in POLDER case (P_{Hertz} = 1100MPa, solid preloaded), important global deviation and instabilities were observed on average torque unlike RT/Duroïd 5813 furtive transient increases. This is in contradiction to steady state phases reported by ESTL for PGM-HT [7].

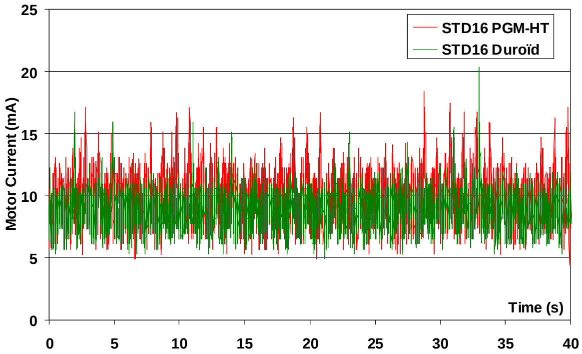

Figure 16 STD typical motor current comparison for RT/Duroïd5813 and PGM-HT

5.2 Tribological interpretation : different behaviors

Previous RT/Duroïd 5813 heritage and end of life expertises realized by CNES tends to rise that tribological behaviors of RT/Duroïd 5813 and PGM-HT are significantly different. As illustrated on figure 17 showing balls and cages after lifetests using RT/Duroïd 5813 bearings, cages wear is very important and balls are smoothly coated by dark grey tending to brown film. This is characteristic of a stable PTFE/MoS_2 transfer film. These differences lead to the following hypotheses on tribological behavior of PGM-HT :

- Influence of PGM-HT wear rate : as presented previously (cf. § 4.3), PGM-HT wear was very limited during lifetests analyzed in this paper. This comment was also widely reported in the literature even for pin on disk elementary tests. An explanation can be correlated by both PGM-HT low elastic modulus (6 times lower than RT/Duroïd 5813 one) and its microstructure. Thus, big glass fibers observed on PGM-HT might prevent MoS_2 wear particles release necessary to lubrication (size and quantity). In the same way, low elastic modulus might cause cage structural accommodation to defect or particles at sliding interfaces. Both phenomena can have a synergistic action to limit PTFE/MoS_2 generation.

- Influence of potential wear particles : in the case of wear particle generation, the coarse PGM-HT microstructure leads to big particles compared to those generated by RT/Duroïd 5813. Due to their size, these particles will not probably go into the ball/race contacts and might not adhere to tribological surfaces. In the same way, any material chunking might have consequences on torque noise because of surface morphology and rugosity increase at sliding interfaces.

- MoS_2 transfer film establishment/stability ? According to expertise, it seems that steel wear occurred even though Hertzian pressure are below 1200 MPa. Like low cages mass loss, it suggests that PGM-HT cages were not able to release enough PFTE/MoS_2 particles and to create a sufficient dual transfer. In the same manner, it has to be further investigated if discrepancies between vacuum and dry nitrogen lifetests on STD are due to non lubricated metal/metal contact behavior.

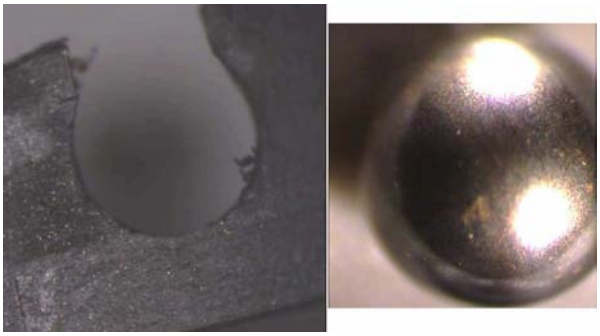

Figure 17 Ball and cage after lifetest using RT/Duroïd 5813 cage

6 CONCLUSIONS and LESSONS LEARNED

For this study, two mechanisms successfully qualified with RT/Duroïd 5813 were submitted to new lifetests with PGM-HT caged bearings. The aim was to assess the capability of PGM-HT to replace RT/Duroïd 5813 on completely representative devices rather than on elementary test samples.

In a first approach, both lifetests realized with PGM-HT under dry nitrogen did not show major discrepancies in terms of peak torque values compared to RT/Duroïd 5813 ones. Nevertheless, in 1st STD lifetest (P_{Hertz} ~600MPa, elastic preloaded) and POLDER case (P_{Hertz} = 1100MPa, solid preloaded), an important global deviation and instabilities were observed on average torque. Thus, unlike RT/Duroïd 5813 transient increases, no stable phase was observed on PGM-HT for POLDER case.

In addition, tribological expertise and interpretation of these lifetests lead us to the conclusion that RT/Duroïd 5813 replacement by PGM-HT must be further investigated. This conclusion is mainly based on materials microstructures and tribological behaviors differences. PGM-HT microstructure is indeed much coarser the RT/Duroïd 5813 one and their mechanical properties are different. Whereas RT/Duroïd5813 can be considered as a good lubricant source with the ability to generate a stable PTFE/MoS_2 transfer film, no transfer film was observed with PGM-HT caged bearings. Steel wear occurred with no guaranty of resistive torque stability especially under high vacuum.

Finally, in addition to the need of new tribological work on PGM-HT presented above to consolidate its performances and operating modes, designers should pay attention to friction torque evolution observed on PGM-HT caged bearings. Mechanisms should be submitted to lifetime test as soon as possible in development phases. Although such an exhaustive test phase, particular attention should be paid to motorization margins and additional margins to classical ECSS ones might be used if no warranty on test representativity in insured (depending on torque values and evolution).

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