Lessons Learned on Cryogenic Rocket Engine's Gimbal Bearing Lubrication Selection

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Abstract

The bearings for a gimbal of a cryogenic upper stage rocket engine are highly loaded, exposed to corrosive environment and have to cope with a wide temperature range down to cryogenic temperatures. "Cronidur 30" steel was chosen for the bearing material. To satisfy the demand of low friction moment under these conditions a tribological concept should be found. This paper describes the selection process for the tribological concept suitable for this specific application that resulted in the selection of sputtered lead as lubricant for the gimbal bearings.

Introduction

Austrian Aerospace has the privilege to develop the gimbal for the next generation upper stage engine of the ARIANE 5 Launcher family, the VINCI engine. The challenges for bearings of a gimbal for a cryogenic upper stage rocket engine are:

- high loads due to the transmission of the thrust of the engine,
- high reliability requirements for both environments: atmospheric conditions and space vacuum,
- wide temperature ranges down to cryogenic temperatures,
- considerable number of only small oscillatory cycles,
- low friction and wear requirements.

Previous gimbals use common bearing materials similar to the bearing materials used in today's satellite mechanisms such as SAE 52100 or AISI 440C steele. FAG (FAG Kugelfischer AG, Germany) recently developed a novel bearing steel "Cronidur 30" which combines the advantage of high load capability with the advantage of high corrosion resistance, better than AISI 440C. Moreover "Cronidur 30" demonstrates excellent mechanical properties at cryogenic temperatures [1]. For this reason we selected "Cronidur 30" as the material for the gimbal bearings.

We expect "Cronidur 30" to increasingly become the substitute for today's commonly used bearing steels for space mechanisms. Currently little information is available and little experience exists concerning lubrication of "Cronidur 30" under space environment and specifically the behaviour of solid lubricant coated bearings made of Cronidur 30.

Keeping in mind the needs of the rocket engine gimbal bearing, Austrian Aerospace had the task to investigate possible lubricants; to make a trade between those candidates by aid of development tests;to select a suitable lubricant; and to qualify the chosen tribological system for the use on the ARIANE 5 launcher.

This paper details the development work performed to date (December 2003).

Description of the Mechanism

The main functions of the gimbal are to fix the engine in its defined position, to transfer the thrust and all inertial forces from the engine to the stage and to allow the gimbal operation.

The gimbal consists mainly of an engine-side bracket, the cardan cross and the stage-side bracket, connected by two pairs of bearings.

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Needle roller types were selected due to the high load capability and the low friction moment under the specified environmental conditions, combined with a small envelope.

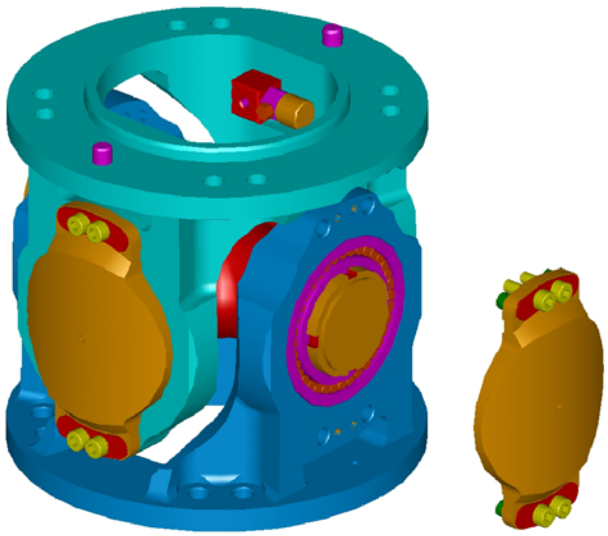

Figure 1. Gimbal design

The bearings are kept as small as possible due to the stringent mass and envelope restrictions. This leads to high Hertzian contact pressures between the needle rollers and the bearing rings. The Hertzian pressure will be more than 4000 MPa.

Demands on the Tribological System

The main demand on the tribological system formed by the bearing's inner and outer rings, needle rollers and the lubricant is to attain a low coefficient of friction during the whole lifetime of the bearings and after exposition to environmental attacks. This low coefficient of friction shall be attained despite the high Hertzian pressure and for operation in air as well as in vacuum.

The tribological system shall be compliant to the following requirements:

- compatibility to corrosive media, LOx and LH_2, and the operating temperature range that includes cryogenic temperatures.
- material compatibility to the bearing material Cronidur 30.
- no impact on the bearing precision
- the application process shall be suitable for the needle roller geometry selected.

Selection of the Lubricant Candidates

The decision either to operate without a lubricant or to use a lubricant was driven by the risk of cold welding under vacuum environment using a full "Cronidur 30" design comprised of rollers as well as races made of "Cronidur 30" without a lubricant. To avoid this risk the use of a ceramic material for the rollers was discussed. However utilizing ceramic needle rollers is not feasible for the gimbal bearings as bending stresses in the needle rollers would possibly cause destruction of ceramic needle rollers.

Fluid lubricants are not usable for the gimbal bearing lubrication at cryogenic temperatures and heating of the bearings is not possible. The operating temperature range goes down far below -75°C, which is known to be the lowest temperature limit for fluid lubricants. For these reasons a dry lubricant was selected.

Dry lubrication by sputtered silver was first discussion due to the vast heritage of the use of silver as lubricant in space mechanisms on conventional bearing steels. However a systematic approach was taken.

For a pre-selection, 27 dry lubricants were assessed in terms of friction coefficient, wear rate in air and vacuum, applicability for high precision bearings, heritage, temperature range, corrosion and electro-galvanic aspects and development risk for the application process.

Without going into more details concerning this pre-selection, the remaining promising candidates of this pre-selection were:

- Sputtered MoS_2 (Molybdenum Disulphide)
- Sputtered Ag (Silver)
- Sputtered Pb (Lead)
- Air-blasted WS_2 (Tungsten Disulphide).

Trial depositions with these candidates were performed on representative rollers of “Cronidur 30”.

Performance Testing of the Pre-Selected Lubricant Candidates

No information could be found in the literature regarding the behavior of these candidates together with “Cronidur 30” under corrosive environment. Therefore environmental tests were carried out as a first step. To investigate the behavior of the coatings applied on the “Cronidur 30” base material under corrosive environment, a salt spray test was performed as an accelerated test simulating environmental conditions that may occur during storage, integration, transport and test of the gimbal itself and of the gimbal integrated on the engine.

A transparent test rig was manufactured that held the sample rollers on both ends. The samples were exposed to a salt fog for two cycles comprising of 24 h with and 24 h without salt fog (pH=6.85±0.35) each at 35°C±1°C.

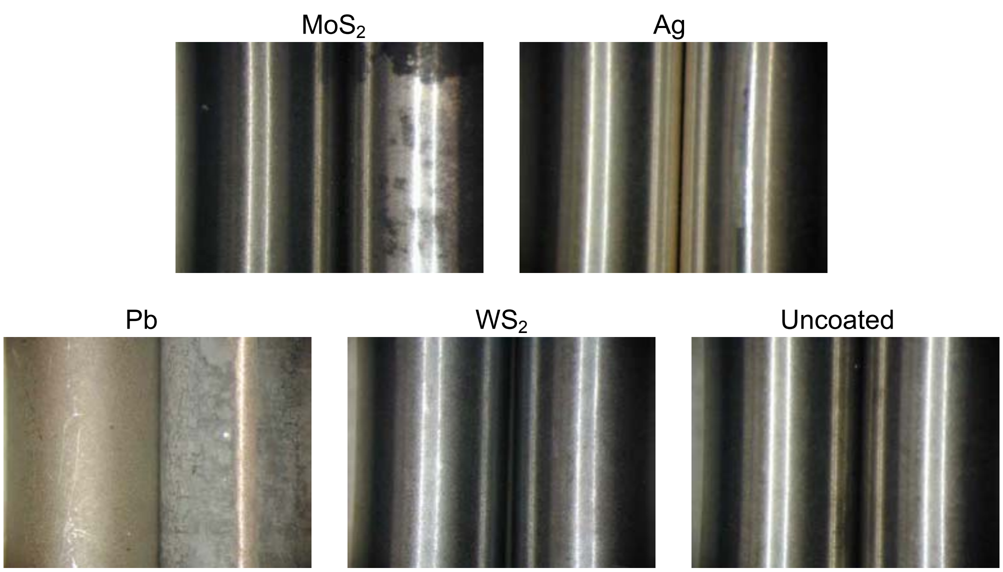

Figure 2. Salt Fog Test Results

In Figure 2, the results of the environmental tests are shown. The pictures show magnifications of two roller surfaces of each candidate of un-tested rollers (left roller surface in each picture) and tested rollers after exposure to the environmental test (right roller surface in each picture):

A visual examination showed the following results:

- MoS_2 on “Cronidur 30” (upper row left): Massive removal of the lubrication layer.
- Ag on “Cronidur 30” (upper row right): Undistorted Ag covered surfaces kept unimpaired.
- Pb on “Cronidur 30” (lower row left): Formation of a lead salt layer.
- WS_2 on “Cronidur 30” (lower row middle): No visible degradations.
- Uncoated witness sample of “Cronidur 30” (lower row right): No visible degradations.

For this reason, the MoS_2 coating was not an option for the gimbal lubrication.

To gather information about galvanic corrosion, the test was performed on samples with distorted coatings. The upper end of the rollers kept uncoated to simulate a distortion of the coating.

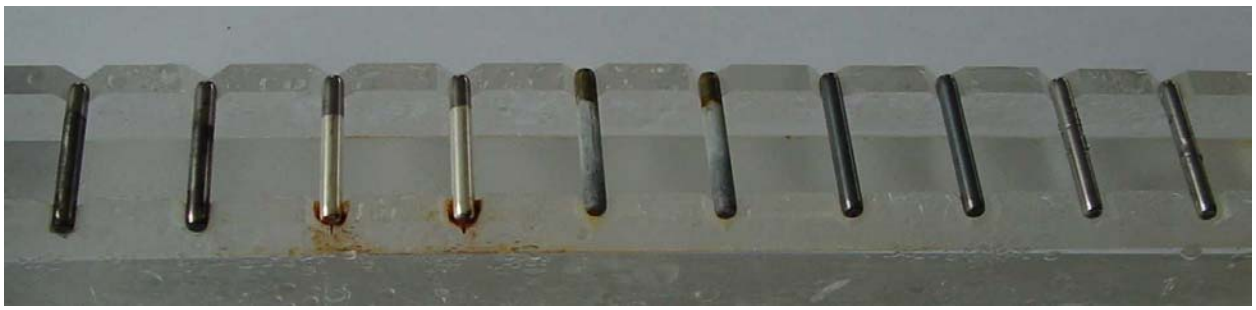

Figure 3. Salt Fog Test Results of Samples With Distorted Coatings

In Figure 3, the test specimens are shown after the performance of the test. Two samples of each kind are shown in the picture: 2x MoS_2, 2x Ag, 2x Pb, 2x WS_2, and 2x uncoated samples of “Cronidur 30” (from left to right).

Surprisingly the silver-coated samples showed indications of severe galvanic corrosion in combination with the “Cronidur 30”.

XRF examinations were performed by ESTL to verify this result. One of the results was that the XRF of the red colored areas of the silver coated samples suggested a slightly higher concentration of iron. This result confirmed that galvanic corrosion has occurred. For this reason, the silver coating was not an option for the gimbal lubrication.

The XRF examination of the lead coated sample showed that still enough lead was present to provide lubrication. As lead salt itself is soft and will be cracked up and embedded between the remaining lead no negative impact on the lubrication effect is to be expected.

Besides the environmental loads on the tribological system, there are demands on the friction coefficient and the load capability to be satisfied. For both remaining candidates, WS_2 and lead literature describes sufficiently low friction coefficients for the intended operation profile as well for operation in air as in vacuum. Further investigations on the WS_2 showed that the coating is not appropriate at the high Hertzian pressures that occur in the gimbal bearings in the light of the bearing life time requirements.

Result and Outlook

The result of this investigation and the test campaign was that only the sputtered lead coating showed the potential to act as lubricant for the gimbal bearings. This selection is based on:

- The proven compatibility of the lead coating with the environmental loads, as concerns our specific application.
- The known and demonstrated excellent performance of a lead coating under high mechanical surface pressures and under oscillatory motion [2].
- The vast heritage of the standard sputtering lead coating process by ESTL (European Space Tribology Laboratory, UK).
- The lead's compatibility to oxygen. If oxidation should occur a lead-oxide layer is formed which encapsulates the underlying lead. This lead oxide itself has lubricating properties and acts as lubricant itself. Moreover the thickness of the oxide layer (about 20nm) is small compared to the coating thickness.

Currently the qualification of the coating (performed by ESTL) and manufacturing of the bearings for the first 4 gimbal models (performed by FAG) is under way and representative friction measurements are planned beginning of August 2004.

These friction measurements will include investigations on the impact of oxygen, life time behaviour of the coating, and overload testing of the bearings.

Conclusion

Based on investigations of a variety of lubrication alternatives showed that for the specific application on the gimbal requiring survival under high Hertzian contact stresses and high resistance to environmental impacts it was determined that lead lubrication performs best on the "Cronidur 30" substrate.

In contrast to the expectations that

- Silver coatings which is widely used on conventional bearing steels on space application would perform in an excellent manner, and that
- "Cronidur 30" material is fully resistant to corrosion

It turned out that

- Silver coating on a "Cronidur 30" substrate leads to severe galvanic corrosion problems
- Severe corrosion effects can occur under certain circumstances even though "Cronidur 30" steel has excellent corrosion resistance compared to other bearing steels.

References

1. Trojahn, W. et al. "Progress in Bearing Performance of Advanced Nitrogen Alloyed Stainless Steel, Cronidur 30." *Presented at the 5th International ASTM Symposium on Bearing Steels, New Orleans, Louisiana, USA - Nov. 19-21, 1996*
2. N.N. "Space Tribology Handbook, 3rd Edition." *AEA Technology plc - ESTL Cheshire, UK, 2002*

Remark

Ariane 5 is an ESA program, managed by CNES, prime contractor of VINCI is SNECMA.