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WEAR-RESISTANT BALL BEARINGS FOR SPACE APPLICATIONS

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ABSTRACT

Ball bearings for hostile environments have been developed. They consist of normal ball bearing steel parts of which the rings are coated with hard, wear-resistant, chemical vapor deposited (C.V.D.) TiC. Experiments in ultra-high vacuum, using cages of various materials with "self-lubricating" properties, have shown that such bearings are suitable for space applications.

ESA has considered using such treated ball bearings.

The results of different laboratory tests undergone by the ESA Meteosat Radiometer Focalising mechanism, which contains 6 coated bearings, are promising, and are summarised.

INTRODUCTION

Ball bearings are required for operation in hostile environments, for example, in corrosive media, under radioactive radiation, at elevated temperatures, in space, etc... They must be perfectly reliable as in most of these environments few or no parts can be replaced.

This paper deals with the development of ball bearings for space applications. Several solutions have been proposed; the use of bearings made of special high speed steels, cemented carbides, or various hard, wear-resistant materials other than steel have brought some improvements. We, at the LSRH, have tried to resolve the problem by coating standard commercial steel ball bearings with hard, wear-resistant TiC layers by C.V.D. (Chemical Vapor Deposition),

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and by using cages of various materials with "self-lubricating" properties (1,2). The ESA considered these bearings of interest for space applications, e.g., in its Meteosat programme.

In the following the characteristics of the bearings are described and the procedure for obtaining them is given in brief. Finally, some of the planned space applications are mentioned; some tests undergone by the various mechanisms in which such treated ball bearings have been used are also given.

CHARACTERISTICS OF THE BEARINGS

For rolling and sliding contacts during continuous and interrupted operation it is important that the materials of the partners are of a different nature. In vacuum particularly it is preferable to have metal - ceramic rather than metal - metal contacts in order to avoid microwelds and diffusion. Only one of the partners need therefore be treated with TiC, i.e., the balls or the rings. The combination "uncoated balls - coated rings" is preferable for small diameter bearings. For larger diameter bearings the contrary is true. In fact, the rings undergo distortion and/or deformation during C.V.D. For larger diameter rings the deformation can be so important that correction by mechanical means becomes impossible without removing the TiC layer (5 - 10 μm). At the moment development work is being done for the application of hard, wear-resistant TiC coatings to larger diameter ball bearings.

For most applications hard coatings are only of value if the supporting substrate material is also hard. Hence, only hardenable steel, cemented carbides or ceramic materials are suitable. For the ball bearings described here, a hardenable stainless steel (AISI 440 C) was chosen because:

- the rings and spheres can be machined from this steel, thus the existing ball bearing production know-how can be applied and the overall costs reduced;
- this steel is suitable for the C.V.D. of TiC; its composition (∿1%C; ∿17%Cr) enables air quenching to a hardness of about 62 Rc; its deformation and/or distortion during thermal treatment can be kept within reasonable limits.

During the last years the know-how for the C.V.D. of TiC on C and Cr containing steels has become well established (3). Such coatings are very friction-and wear-resistant and show no measurable wear from adhesion during friction against metals (4). The composition of TiC can vary greatly between $TiC_{0.3}$ and almost the stoichiometric composition TiC (5). The mechanical properties of single crystals and of sintered hot pressed TiC are given in (6). An important property of TiC for its application to bearings is its hardness. In Table 1 the comparative hardnesses of several ceramic materials are given on a schematic scale.

PROCEDURE FOR OBTAINING TiC COATED BEARINGS

The TiC coatings are applied to polished, finished bearing rings. This is important since the surface roughness increases during C.V.D., and due to the hardness of TiC it is difficult and delicate to polish the races.

The C.V.D. of TiC is performed at the LSRH. The machining, thermal treating, polishing and assembling of the ball bearings are carried out by experienced manufacturers. In the case of the small diameter bearings which are discussed here, the manufacturing work, and some testing of the finished products, was done by RMB (Roulements Miniatures, Bienne, Switzerland).

The C.V.D. of TiC is achieved by the interaction of a volatile Ti halide with H_2 and CH_4 at a high temperature (2,7):

$$TiCl_4\ (g) + CH_4\ (g) \xrightarrow{H_2;\ 800 - 1000^{\circ}C} TiC\ (s) + 4HCl\ (g)$$

The deposition rate depends on several parameters and can vary from 1 to 5 micrometers per hour. Figure 1 shows a scanning electron microscope picture and the microprobe analysis results of a section through a TiC coating and its AISI 440 C steel substrate. The steel is in the quenched state, i.e., the mixed Cr-Fe carbide grains are dispersed in a martensitic matrix.

A very important aspect in the manufacture of high precision bearings is the fact that in the steel the phase changes "pearlite → austenite" and "austenite → martensite" are accompanied by volume changes. If the heating and cooling is not done according to the cycles prescribed (8), disastrous distortion might occur (9).

The C.V.D. process is characterised by the fact that the quality of its products is influenced by many parameters of which some important ones are: the pressure, total gas flow, gas composition, temperature and its profile and cycle, load density and its arrangement in the reactor. A slight change in one of these operating conditions can have a drastic influence on the characteristics of the TiC coating. For the bearings used in the Meteosat Programme, a vertical C.V.D. reactor of 120 mm I.D. was used; for each treatment a total of 36 pairs of bearing rings were evenly spaced upon 6 different levels. Despite the difficulties encountered in keeping the many parameters constant, the reproducibility of the coatings was more than acceptable. Due to the thermal treatment a certain number of rings underwent too large a distortion and had to be rejected. Five reactor loads were necessary to produce the total amount of ball bearings for the Meteosat programme.

The TiC coating thicknesses averaged over the 6 levels are indicated in Table 2 for the 5 C.V.D. treatments. These results were obtained by sectioning a pair of rings from each level after each treatment, and by examining them in an optical microscope. These results show that by taking normal precautions, it is possible to obtain results which are sufficiently reproducible for the production of TiC coated rings for small diameter ball bearings.

APPLICATIONS

1. Solar Wind Composition Experiment (Apollo)

With its Solar Wind Composition Experiment the University of Bern, Switzerland, participated in Apollo experiments on the moon. A metal foil was unrolled manually by the astronauts of the first five Apollo landings, exposed to solar radiation and rolled up again. For these manual operations a device with standard bearings was used. For Apollo 17, however, an automatic foil roller was developed. At the start of the experiment the foil was to be unrolled manually, then by means of a timer the foil was to be rolled up in a stepwise manner, at fixed time intervals. In order to ensure a reliable operation, TiC coated bearings were considered, the characteristics of which are as follows:

Types: two O.D. 13 mm, I.D. 6 mm, and one O.D. 13 mm, I.D. 4 mm
Rings: AISI 440 C steel/ 3 µm TiC
Balls: AISI 440 C steel
Cage : AISI 440 C steel/ PTFE coated (photopolymerization)

The device which was provided with the bearings described above was submitted to the European Space Research and Technology Centre for operational and vibration tests. The operation of the mechanism was checked in ultra-high vacuum thermal and solar simulation conditions. In another testing programme the Solar Wind Experiment package was subjected to sinusoidal and random vibrations in 3 mutually perpendicular axes, according to NASA specifications. The performance proved to be extremely satisfactory (10,11). This modified Solar Wind Composition Experiment, could not, however, be flown as part of the heavy Apollo 17 programme.

2. Meteosat Radiometer Focalisation Mechanism

The Meteosat telescope will be used to take pictures of the Earth and clouds from a geostationary satellite. In order to obtain good quality images the focus of the telescope has to coincide at all temperatures with the detector. This is assured by a mechanism which causes the translation of a reflecting dihedron. The focusing device is manufactured by MATRA ENGINS, France. Figure 2 shows a schematic view of the mechanism which consists of a step-by-step motor, 5 to 1 reducing gears and a screw-bolt system. The rotor, intermediate pignon and screw are mounted on ball bearings (Type O.D. 13) manufactured by RMB; the rings are coated with TiC. The bearings are prestressed to such an extent that there is no risk of shocks during the lift-off. The mechanism has been tested by MATRA ENGINS and CNES

2.1. Tests by MATRA ENGINS (12)

A mechanism was activated periodically in ultra-high vacuum. Each test cycle consisted of a complete focalisation range plus return. It was impossible to measure the torques induced by the bearings; variations in the total resistance were, therefore, followed by measuring the starting voltage of the step-by-step motor.

In Table 3 the programme followed for this series of tests is given. The number of revolutions achieved during the programme exceeds that which the mechanism is required to perform in space. These lifetime tests have not yet been completed, no visual examination of the bearings has therefore been done up till now.

During the first 20 focusing cycles in ultra-high vacuum there was a slight increase in the resistant torque, to a level close to that measured in the laboratory atmosphere. This increase never reached 30% of the low values obtained at the start of the U.H.V. testing. The safety margin of the mechanism was about 6, since the nominal voltage available was 10 V. In order to see if the torque increased after one lifetime, the tests were continued until twice the expected lifetime of the mechanism had been attained. The important conclusions of these tests are that the resistant torque in U.H.V. is not greater than that in normal atmosphere, and that it does not increase after an immobility of 30 days.

2.2. Tests by CNES

These tests are complementary to those done by MATRA ENGINS and are aimed at quantifying the resistant torques of the bearings, the behavior of the torque and the deterioration of the bearings, under the conditions in which the mechanism will be required to operate.

The resistant torque of the preloaded bearings was continuously measured by means of a microbalance (13). In order to take into account the different stresses the motor and screw bearings will be required to withstand, two types of tests were carried out:

- screw bearing type: characterised by continuous rotation at low speed (90 rph), and by a very high preload (7daN);

- motor bearing type: characterised by intermittent very high angular acceleration (typical for a step-by-step motor) and a high preload.

In order to take into account the integration, qualification and acceptance tests of the mechanism, and its use during flight, both types of tests were performed in two uninterrupted stages; one in air and the other in U.H.V. The rotation direction was alternated periodically. In Table 4 the conditions under which the tests were performed are given. The length of the tests was determined by taking into account the worst configuration and by multiplying by a safety margin of 2.

Three types of information were obtained from each test:

- the behavior of the torque measured continuously with the microbalance; every 15 minutes the average and maximum torques were recorded and plotted against time;
- the comparison between the individual bearing torques, before and after the tests, according to the U.S. standard MIL.STD.206;
- SEM analysis of the bearings after the tests; identification of the deposits on the races by means of X-ray spectrometry.

The results obtained with the <u>screw bearings</u> are as follows:

- In air, after a short running-in during which the torque increased, the latter stabilised between 40-50 g.cm; the average torque was relatively stable and the maxima were about 50% above the average. In vacuum, after a sudden increase of the torque there was a running-in corresponding to a decrease in the torque which became stable between 25-30 g.cm. The torque was noisy and the maxima were about 100% above the average. This can be seen in Figure 3.
- The ratio of the averages of the individual torques of the bearings, before and after the tests, was between 1 and 2.
- SEM analysis showed that despite the very high preload the TiC coating did not deteriorate, but that a double transfer (cage → ball → rings) of the Ag-In lubricant occurred. The Ag-In coating on the surfaces of the balls was uniform, but only particles of this material were present on the races.

The results obtained with the <u>motor bearings</u> are as follows:

- In air, the torque increased continuously throughout the tests, from 4.5 to 24 g.cm. The torque presented the same type of noise as the screw bearings in vacuum. The maxima were about 40% above the average. There was no running-in. In vacuum, the torque decreased slowly from 24 g.cm and became stable at about 3-6 g.cm. The torque presented the same noise as in air and the maxima reached 150% of the average torque. This can be seen in Figure 4.
- The ratio of the averages of the individual torques of the bearings, before and after the tests, varied between 15 and 48, signi-

fying an important deterioration of the bearings.

The SEM analysis showed that the TiC coating did not deteriorate, but that there was an excess of lubricating material on the races due to double transfer (cage → ball → rings). The deterioration of the performance of the bearings was significant. Nevertheless, the very severe conditions did not totally destroy them as the TiC coating remained perfectly in place and the cages resisted.

The TiC coated bearings tested satisfied the operational conditions required for the Meteosat Radiometer Focalising Mechanism as the behavior of the wear-resistant coating was good. The Ag-In lubricant should, however, be replaced by one based on MoS_2 or a similar material.

CONCLUSIONS

Hard, wear-resistant TiC coatings obtained by C.V.D. are sufficiently uniform and reproducible for use on rings of small high precision ball bearings. Several space applications for such treated bearings have been proposed. Both bearings and mechanisms using them have been tested in laboratory environment and in actual space simulations, and the results have shown that TiC coated ball bearings are suitable for such applications; no deterioration of the TiC layers was observed.

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Table 1. COMPARATIVE HARDNESSES OF TiC AND OTHER COMMONLY USED CERAMIC MATERIALS.

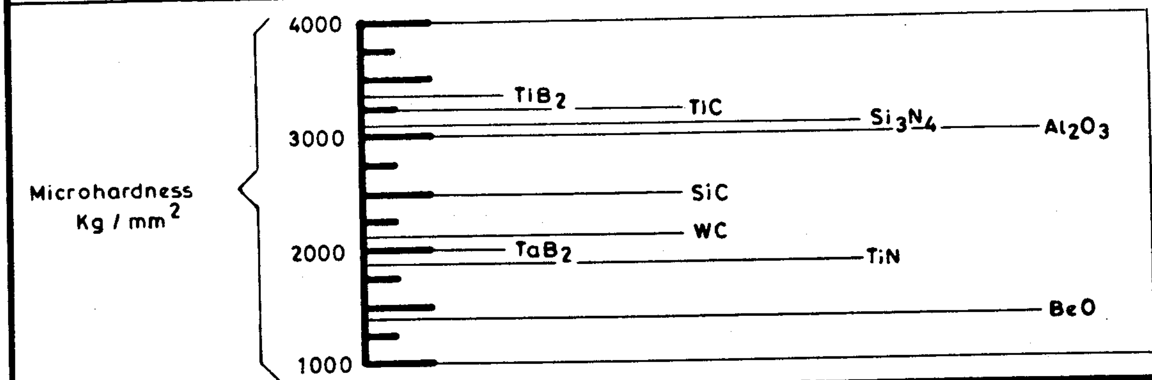

Table 2. AVERAGE TiC-COATING THICKNESSES ACHIEVED DURING THE 5 C.V.D TREATMENTS

TREATED PART	COATING THICKNESSES IN µm				
	C.V.D TREATMENT NUMBER				
	1	2	3	4	5
OUTER RING	6.5 ± 0.5	5.0 ± 0.5	4.5 ± 0.5	4.5 ± 0.5	4.5 ± 0.5
INNER RING	6.2 ± 0.2	4.5 ± 0.5	4.5 ± 0.5	4.7 ± 0.2	4.5 ± 0.5

Table 3. CONDITIONS OF TESTS PERFORMED BY MATRA ENGINS ON THE RADIOMETER FOCALISING MECHANISM.

DURATION (days)	PRESSURE (Torr)	RHYTHM (cycles / days)	NUMBER OF TOURS	
			SCREW	MOTOR
44	$2 \cdot 10^{-6} - 9 \cdot 10^{-9}$	variable	1832	9268
68	$7 \cdot 10^{-9}$	4	1665	8425
30	$7 \cdot 10^{-9}$	1	366	1830
30	$7 \cdot 10^{-9}$	NO	0	0
27	$7 \cdot 10^{-9}$	1	312	1559
	TOTAL		4175	21082

Table 4. CONDITIONS OF TESTS PERFORMED BY CNES ON MOTOR AND SCREW BEARINGS

BEARINGS TESTED	QUANTITY	PRELOAD (daN)	MOVEMENT		UNITS	QUANTITY	
			angular accelerat.	speed		AIR 25±3 °C 45±15 % RH	VACUUM 10^{-9} Torr
MOTOR	6	4.5	very large	1.8 °/<4 msec	motor steps	$6.2 \cdot 10^{6}$	$7.2 \cdot 10^{6}$
SCREW	6	7.0	0	90 rph	number of tours	6150	7074

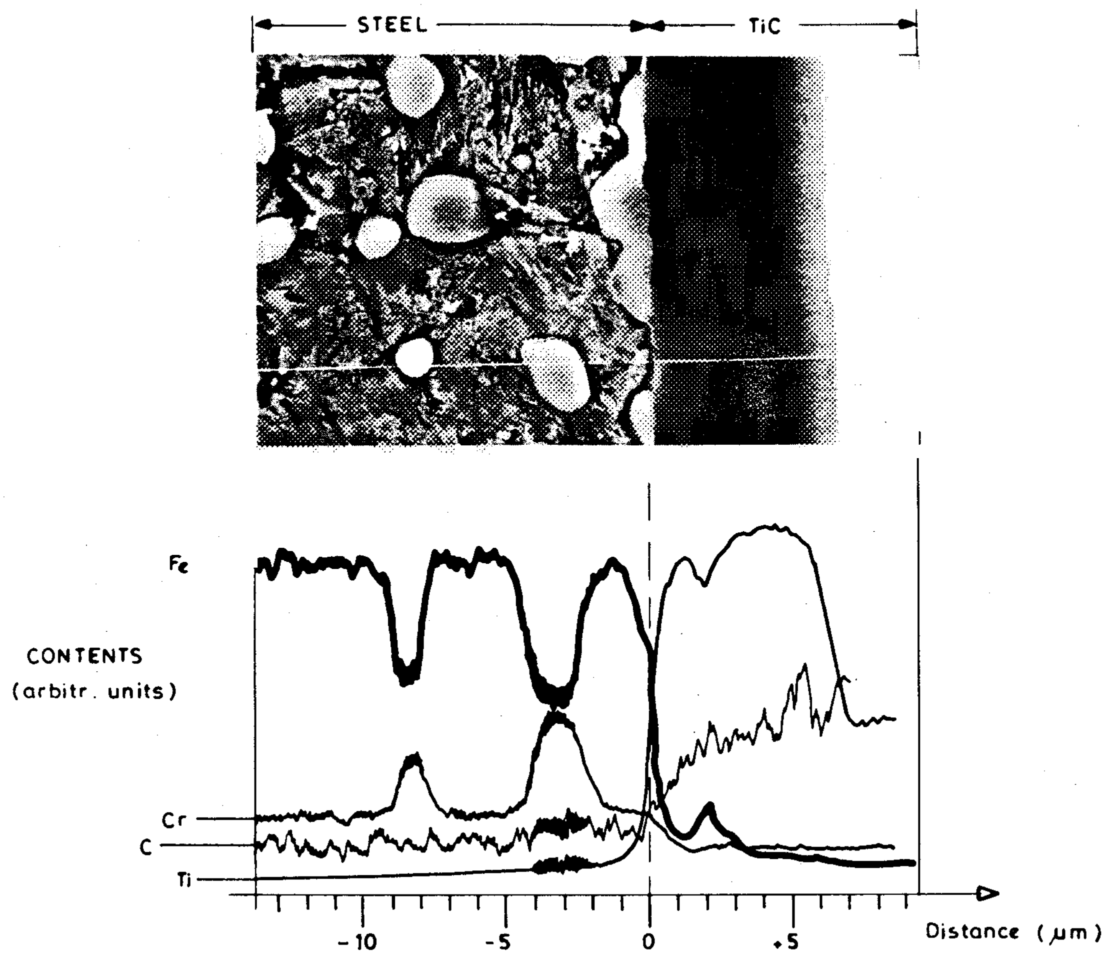

Fig. 1 MICROPROBE ANALYSIS ON SECTION THROUGH TiC COATING AND AISI 440 C STEEL SUBSTRATE.

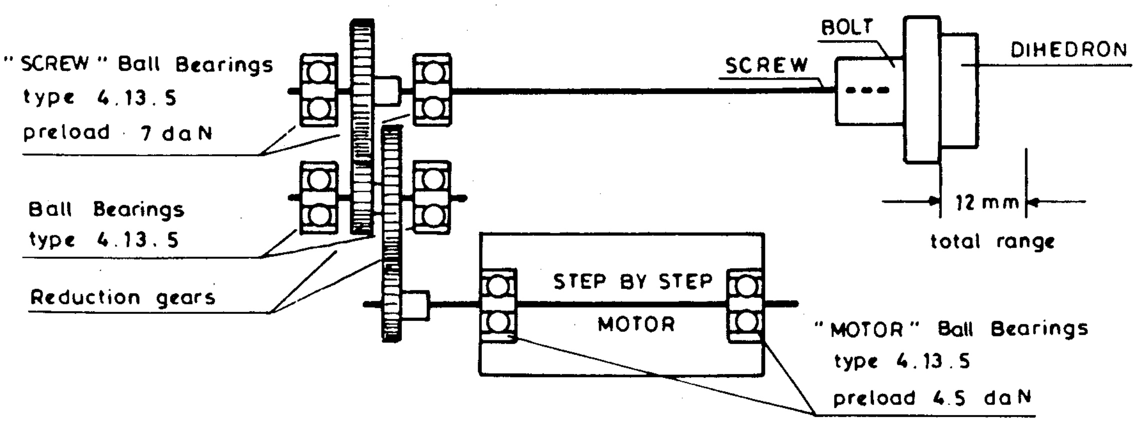

Fig. 2 SCHEMATIC PRESENTATION OF THE RADIOMETER FOCALISING MECHANISM

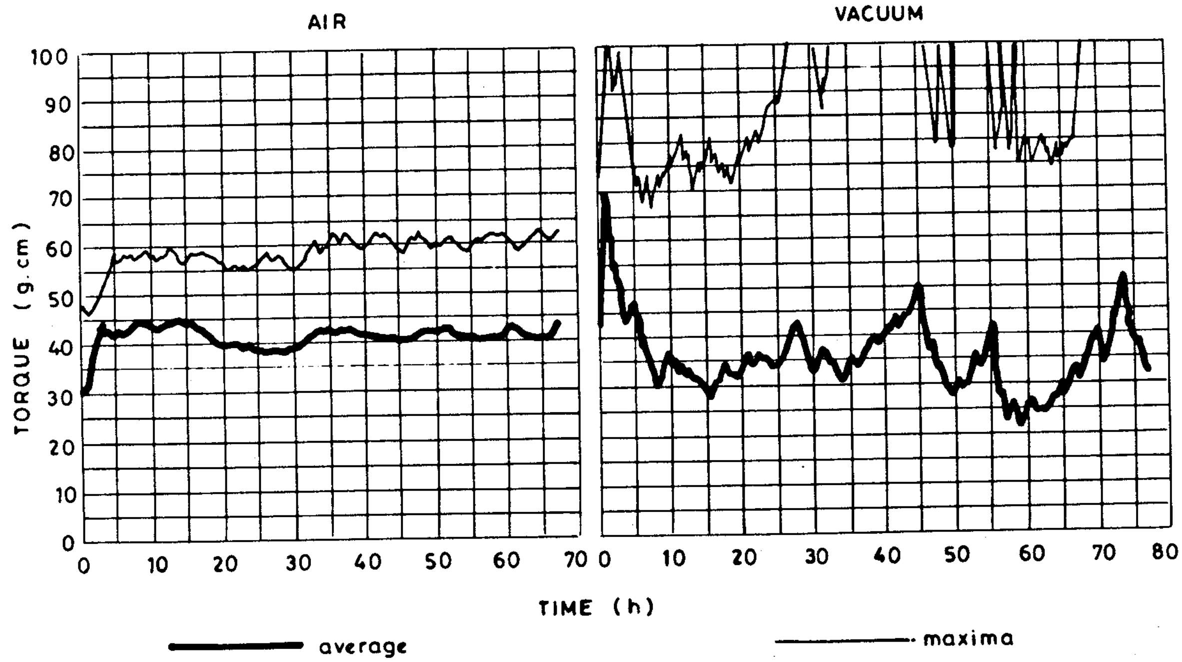

Fig. 3 BEHAVIOR OF TORQUE OF THE BEARING DURING THE SCREW TYPE TEST.

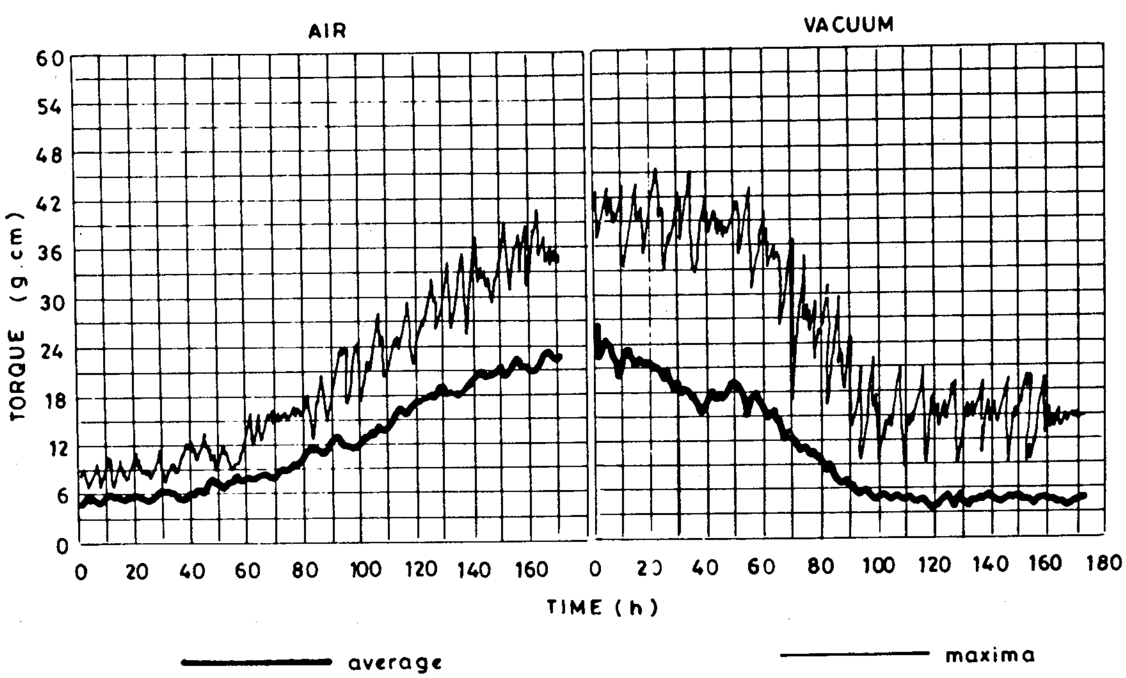

Fig. 4 BEHAVIOR OF TORQUE OF THE BEARING DURING THE MOTOR TYPE TEST.