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SURFACE PROPERTIES ENHANCEMENTS OF Ti6Al4V PARTS FOR MECHANICAL APPLICATIONS

1 - INTRODUCTION

Titanium alloys are widely used in aeronautics because of their low specific weight and their good fatigue properties and in chemical industries because of their good corrosion resistance. Their application in Mechanical Engineering is however hampered by their "poor" scuffing resistance.

An evaluation of the scuffing resistance of the Ti-6Al-4V alloy under pure sliding, pure rolling and combined rolling and sliding conditions, performed for representative loads and speeds, is presented in this paper. A dual approach is used. The materials is first tested as a structural alloy, to examine its "volume" properties as a lubricated gear or roller bearing material. Sliding is introduced in the same tests. The material is then tested under dry friction in a fretting rig. Finally, results with coatings like plasma sprayed carbides and oxides or nitrides obtained by plasma nitriding are presented through their effects on both fatigue life and scuffing.

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2 - TITANIUM ALLOY IN LUBRICATED HERTZIAN (EHD) CONTACTS

2.1 - Generalities

Hertzian contacts are found in ball, roller bearings, cams and gears. These mechanisms are characterised by high contact pressures (> 1GPa) and both rolling and sliding conditions. In most applications, the elastohydrodynamic (EHD) film thickness is of the same order of magnitude as the roughness of the working surfaces (RMS = 0,5 µm). Thus the material used must withstand:

- High contact pressures and thus have high "volume" or bulk resistance.
- sliding velocities and thus have high "surface" resistance.

An evaluation of the performance of titanium alloys as a candidate for such applications must therefore address both "volume" and "surface" aspects of the problem.

2.2 - Volume aspects

The volume aspects will be studied in a high precision disk machine by imposing high contact pressure between two specimens, operating under pure rolling conditions, and separated by a thick elastohydrodynamic film. This is achieved with a high viscosity oil.

2.3 - Surface aspects

Surface resistance will be assessed in two ways:

- under pure rolling conditions but with surface interactions. This is achieved with a low viscosity oil,
- under combined rolling and sliding conditions.

In all volume and surface tests:

- the total rolling velocity ($U_1 + U_2$) is kept constant (Table 1)
- all specimens are identical
- the slide/roll ratio $(U_1 - U_2)/(U_1 + U_2)$ is constant in all sliding tests.

Particulars are given in Table 1.

2.4 - Simulation conditions and disk machine

The running conditions (Table 1) retained for this test are representative of those found in gear for aeronautical applications. Simulation is based on the faithful reproduction of the contact conditions (load, pressure and speed) and materials (base materials, lubricant, atmosphere ...) prevalent at a particular point of the gear profile (Fig. 1). A schematic view of the disc machine is also given in figure 1. It consists of two high speed electric motors mounted on a heavy stand. Tests specimens are fastened directly on each shaft. The first motor is fixed, the second is supported on two hydrostatic bearings and has two degrees of freedom, one to accommodate specimens of different diameters (I) and the other for measure friction (II).

The characteristics of this high precision, high speed machine are given in Table 1.

2.5 - Results

Uncoated Titanium

Various tests were conducted for three parameter combinations (normal load, slide/roll ratio and oil viscosity) and three results representative of:

1) "volume" aspects under pure rolling conditions with a thick elastohydrodynamic (EHD) oil film.

2) "surface" aspects also under pure rolling conditions but with a thin "incomplete" EHD oil film, i.e. when a high surface roughness to oil film thickness ratio ($\sigma c/ho$) prevails.

3) "surface" aspects with a low slide/roll (0.07) but for otherwise the same conditions as those defined in 1.

They are presented in Table II.

Coating tests

In the same running conditions as before, three types of coated titanium samples were tested against a hard steel roll:

N° 4 T6A4V with plasma Cr_2O_3 coating
5 " " " WC "
6 T6A4V ion beam nitrided by NITRUVID

Test results are presented in Table III.

They show that:

- Chrome oxide coating cracks in pure rolling conditions; probably the coating parameters are not according with the test conditions. Internal stresses have introduced microcracks which extend as soon as high pressures are introduced.
- Samples with WC coating or the nitrided samples withstand the rolling conditions without any degradation.

- When sliding is introduced, seizing that appears with uncoated samples doesn't exist.
- After one million cycles a surface deformation appears with carbide coating.
- Small spalling can be observed on the nitrided surface but without volume degradation.

2.6 - Discussion

These results show that under lubricated conditions the "volume" of uncoated titanium alloy withstands the severe contact conditions imposed.

This remains true for WC coating or after nitriding. Only small losses in fatigue life are introduced with these coatings.

The surfaces are not affected by asperity interactions for the high $\sigma c/ho$ ratio and the high test pressure doesn't introduce any failure in the hard surface layer.

When sliding is imposed on uncoated titanium, seizing appears immediately.

Nitriding the surface in choosen conditions or coating the surface with an adherent hard layer like tungstene carbide, avoids scuffing and seizing and makes possible uses with sliding.

Now these coating parameters have to be improved for each condition to withstand for longer test periods or higher sliding conditions.

3 - TITANIUM ALLOY IN "DRY" FRICTION CONTACTS

The now classical friction log, or 3D plot of friction versus both amplitude and number of cycles, is given in figure 2 for the uncoated titanium alloy tested. The imposed fretting running conditions are marked in the figure.

The log is divided in three parts:

1) surface screens or pollution are eliminated. Adhesion between rubbing surfaces, or first-bodies, is strong and scars are formed in less than 20 cycles.

2) damaged zones strain harden and particles are detached after 20 cycles. Compacted debris form a third-body which is trapped in the contact and often leads to a drop in friction. Debris fragmentation and oxidation occur after 120 or 150 cycles. Total separation is obtained after 800 cycles.

3) three-body contact conditions, characterized by a continuous formation and elimination of debris, are generated. Steady-state conditions prevail. Up to 60 µm thick powder beds are noted after 500 000 cycles (Fig. 3).

These frictions logs are similar to those obtained with other metallic specimens, except for the increase in friction noted at the end of the stroke which can reach 30% of the average stroke value. Such increases, which occur between 100 and 500 cycles, were also observed with aluminium alloys but never with steels. At this time a degradation depth of about 30 µm is observed. This degradation stays constant up to 500.000 strokes.

Titanium alloys are known to have poor rubbing properties. This is a dangerous statement to make, as friction and wear are not intrinsic material properties. Indeed in some instances, debris beds protect the bulk alloy which thus appears to have "good" friction and wear properties, even better than steel. In high frequency fretting test for instance, all steels debris is eliminated from the contact, protection is lost and surfaces are damaged while titanium alloy debris beds are held in place by the rises noted earlier where they can separate and protect the first-bodies.

Figure 3 shows the test results obtained with a nitrided sample tested against an uncoated titanium sample. Friction values are lower, their increasing can be explained by the formation of a protective third body layer. This layer protects titanium against scuffing even if parts of the nitrided layer disappears during tests.

Figure 4 shows results obtained by testing the WC coated samples.

Again here, friction values are low, their decreasing in the first step of running can be explained by surface roughness accommodation.

Surface wear is very small. The contact here exists only between surface roughness peaks; their interaction explain the small rise of friction at the end of the strokes.

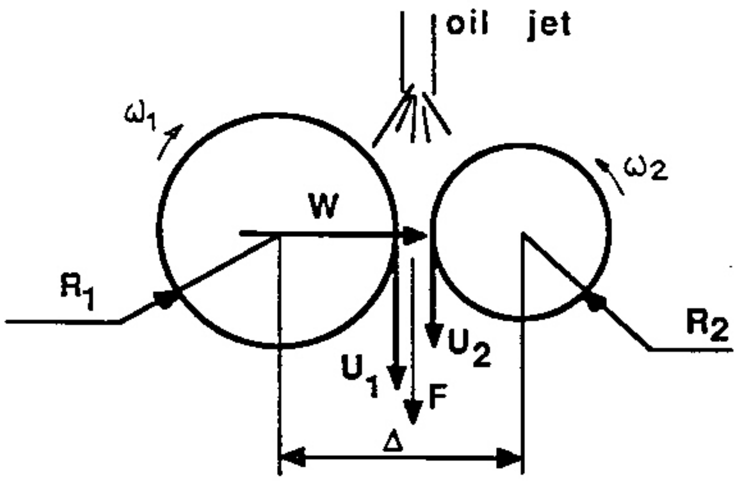
These results show that nitriding or coating titanium with a carbide layer avoid scuffing and give titanium a good wear resistance even at high contact pressures.

4 - CONCLUSIONS

Tribological tests under lubricated hertzian and dry rubbing conditions have been performed on titanium alloys without and with different coatings.

Under lubricated hertzian test conditions, titanium withstands high pressure but sliding induces instantaneous seizing. This scuffing can be retarded to a high number of cycles by protecting the Ti-6Al-4V surface by nitriding or plasma spraying a tungstene carbide coating. Now the choice between these coatings and the optimizing of the deposition parameters: thickness, hardness... have to be done for each specific friction conditions.

PRINCIPLES CHARACTERISTICS OF HIGH PRECISION DISK MACHINE



Center to center distance	Δ (mm)	0 → 100
Disk radius	R_i (mm)	10 → 100
Disk width	(mm)	2 → 15
Rotating speeds	ω_i (rpm)	1500 → 30000
Peripheral speeds	U_i (m/s)	→ 160
Normal load	W (N) /max hertz pressure (GPA)	→ 1500 → 5
Measured friction force	F (N)	3 000
Available power at contact	k (W)	37
Oil jet temperature	T (° C)	→ 200

Any disk material and track roughness

SPECIFIC KINEMATICS CONDITIONS

$U_1 - U_2 / U_1 + U_2$	disk	ω_i (µm)	U_i (m/s)
0	1	8000	15.90
	2	8000	15.91
0.07	1	8570	17.04
	2	7430	14.78

Table 1 - Principles characteristics of high precision disk machine

TEST	CONDITIONS	HERTZ P Gpa	$\frac{U1-U2}{U1+U2}$	EHD film thickness	σc	$\frac{\sigma c}{ho}$	FAILURE
1	Ti-Ti	1,4	0	1,85	0,5	0,27	None 50 10^6
2	Ti-Ti	1,4	0	0,62	0,5	0,81	"
3	Ti-Ti	0,95	0,07	1,62	0,5	0,31	Immediat seizing

Table 2 - Test results

TEST	CONDITIONS	HERTZ P Gpa	$\frac{U1-U2}{U1+U2}$	EHD film thickness	σc	$\frac{\sigma c}{ho}$	FAILURE
4	Ti+Cr2O3/ steel	0,95	0	2,58	1,2	0,45	Scuffing at 10^4
5	Ti+WC/steel	0,95	0 0,07	2,58	1,6	0,63	None 50 10^6 deformation at 10^6
6	Ti nitrided/ steel	0,95	0 0,07	2,58	0,77	0,27	None 50 10^6 Small spalling at 5 10^6

Table 3 - Test results

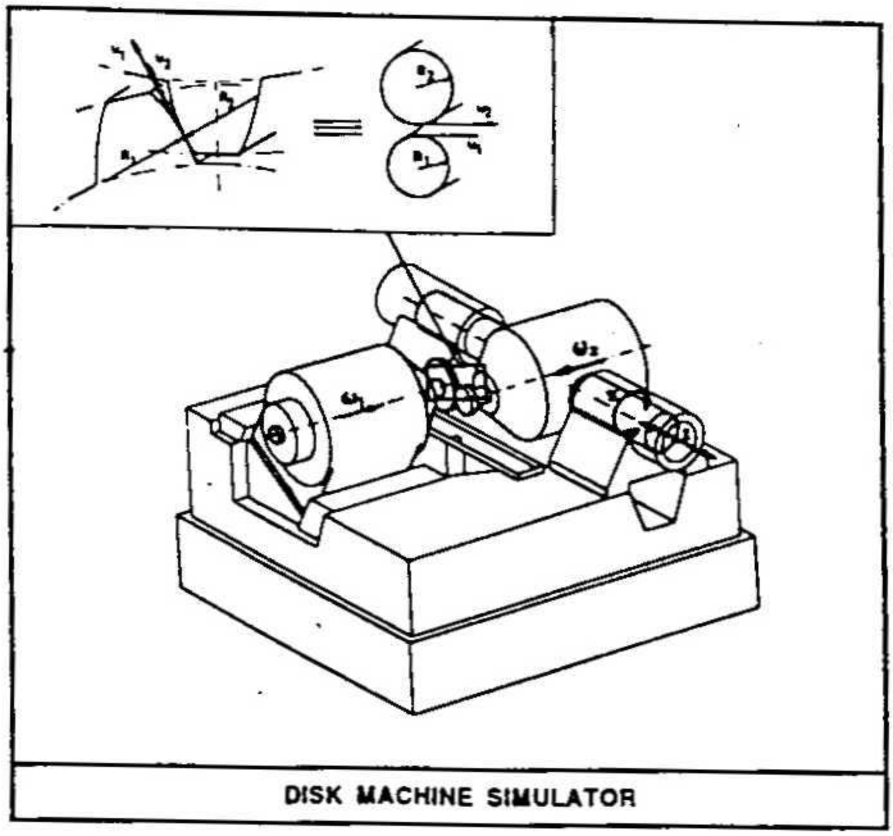


Fig. 1 - Schematic view of disk machine simulator

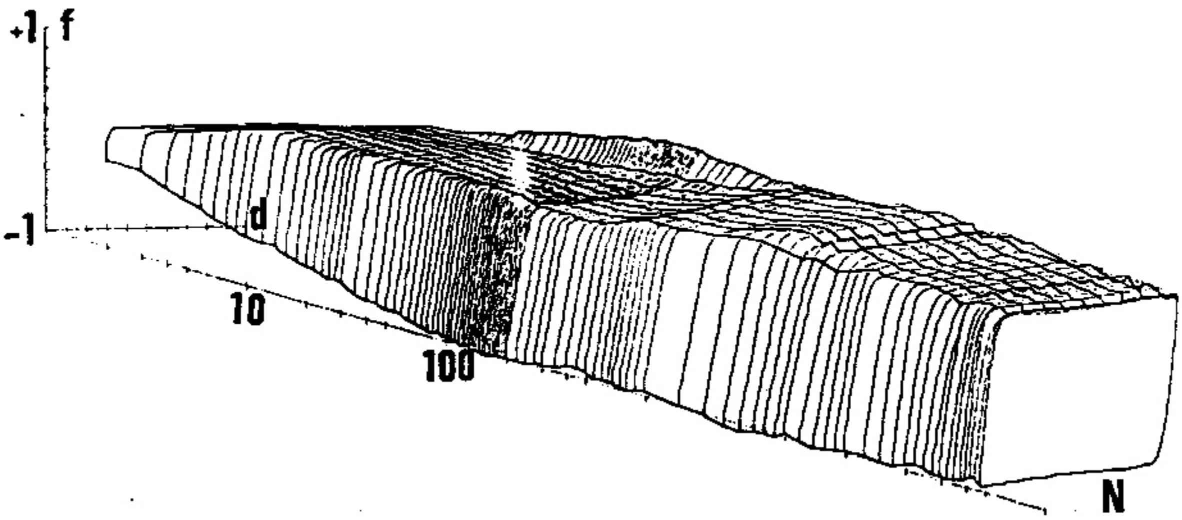


Fig. 2 - Friction log for Ti6Al4V alloy uncoated conditions: load F 500 N, amplitude d ± 50 µm, frequency 1 Hz

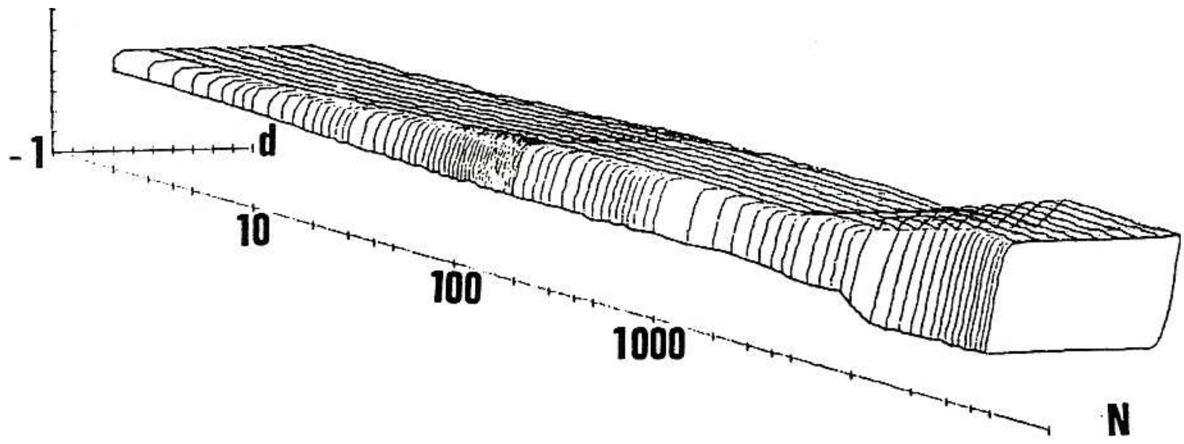


Fig. 3 - Friction log for nitride Ti6Al4V sample

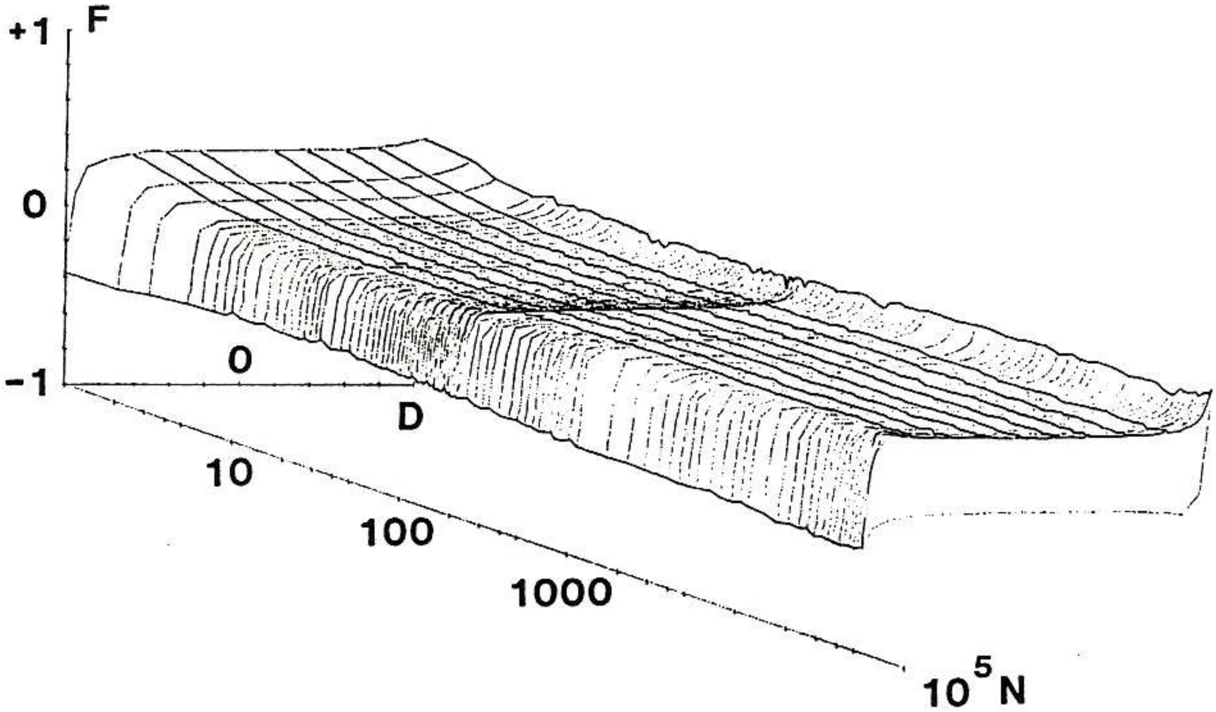


Fig. 4 - Friction log for WC coated Ti6Al4V sample

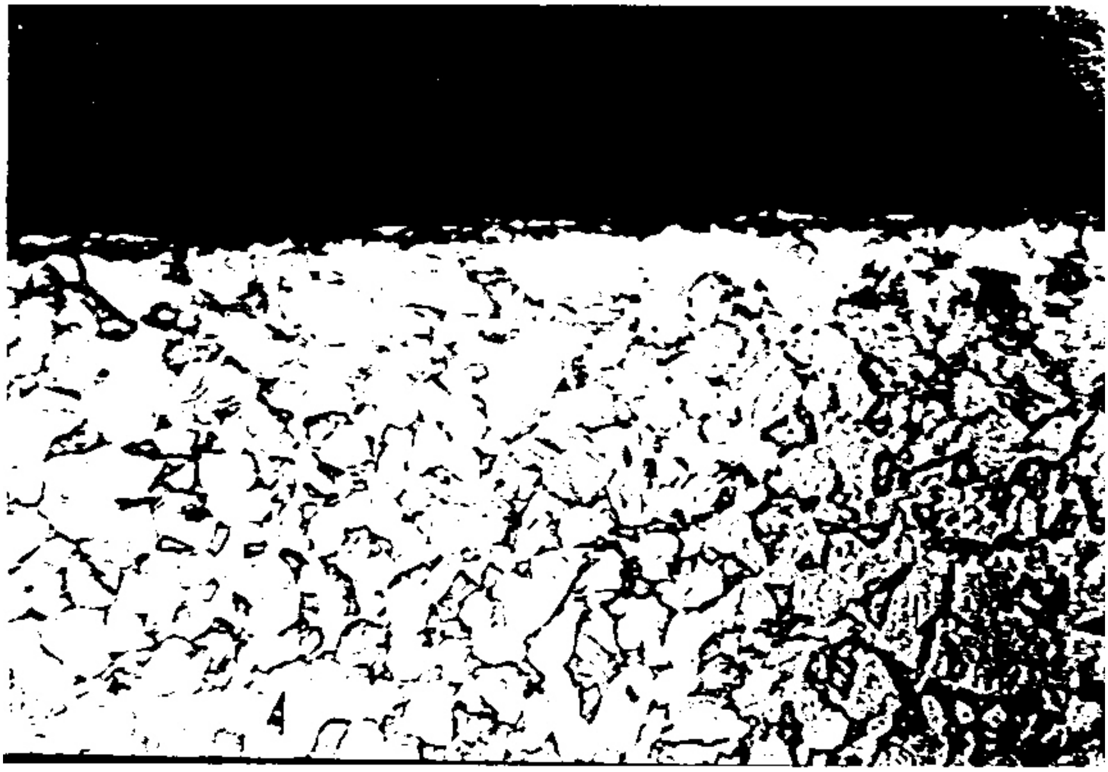


Fig. 5 - Micrographic view of nitride Ti6Al4V tested in friction