SURFACE-TREATED TITANIUM ALLOY GEARS FOR SPACE MECHANISMS

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ABSTRACT

Gears manufactured from titanium alloy offer several potential advantages for spacecraft applications, if their propensity to adhesive wear (galling) can be inhibited. This paper reports on an experimental investigation into the performance of a range of surface treatments on the alloy IMI 318 (Ti-6Al-4V). The gears were tested unlubricated in vacuum, using a "four square" rig. Gear performance was determined by life or number of tooth encounters before failure of the surface treatment rather than by wear depth. Conventional treatments such as nitriding or oxidation have been found to offer limited improved gear life, above that of the untreated alloy. Boronising gave the longest gear life but caused, during treatment, some dimensional growth of the gears. Sputter-deposited coatings of titanium nitride (TiN) were poorly adherent to the substrate and had short lives. Arc-evaporated coatings of TiN gave improved performance until coating fracture and subsequent galling of the titanium alloy occurred.

Keywords: Gears, Surface-Treatments, Titanium Alloys, Vacuum.

1. INTRODUCTION

Titanium and its alloys are widely used in the aerospace industry, with their good strength to weight ratio, adequate fatigue life and corrosion resistance. But, even in an earth environment, these alloys are troublesome when sliding or vibrational contact occurs because of their tendency to galling (adhesive wear) and to fretting damage.

Earlier studies have shown that the sliding properties of titanium alloys can be improved, with varying degrees of success, using diffusion coatings, sprayed hard layers and electroplated coatings (Ref. 1). However, few of these anti-wear treatments are suitable for precision gears because of the variable coating depth or distortion caused. Surface treatments and lubricants to combat fretting of these alloys have also been recently evaluated (Ref. 2).

The emphasis of this work has been to assess a number of surface treatments suitable for gears operating without lubricant and in vacuo. To maintain gear precision and avoidance of post-treatment machining operations, minimal gear dimensional change is essential during thermo-mechanical treatments. Any coating must also strongly adhere and uniformly cover the gear surfaces.

Aluminium alloys have been employed in medium-to-low load gear satellite applications. However, such gears suffer from a strictly limited life before severe adhesive wear occurs (Ref. 3). Titanium alloy gears potentially offer improved performance, if their tendency to gall can be inhibited. Satellite mechanisms are currently under design in Europe where titanium alloy gears have been proposed.

This paper sets out to describe a number of surface treatments suitable for titanium alloy gears and their subsequent friction and wear performance in vacuum. The paper also defines the surface load and life that can be presently achieved with these treatments.

2. GEAR MATERIAL AND SURFACE TREATMENTS

2.1 Gear material

The gears were manufactured from IMI 318 in its annealed condition. Its chemical composition and main properties are summarised in Table 1.

Table 1

Chemical composition and mechanical properties of IMI 318

Composition	90% Ti, 6% Al, 4% V
Proof stress (0.2%)	930 MN/m^2
Tensile strength	1030 MN/m^2
Young's modulus	106 GN/m^2
Hardness	320 HV
Density	4450 kg/m^3

2.2 Surface treatments

Five surface treatments were evaluated. Thei[r] main characteristics are shown in Table 2.

Tifran (Ref. 4) is a commercially available treatment for titanium alloys. It is based on gaseous diffusion into the surface, producing a hard layer consisting mainly of titanium oxide. Teer (Ref. 5) reports hard, wear resistant surfaces are produced on titanium alloy by ion-plating with aluminium. The effect of ion bombardment and high treatment temperature produces an interface of titanium-aluminium solid solution, further hardened by the formation of $TiAl_3$ precipitates.

Titanium alloys can also be nitrided producing a thin layer of titanium nitride (TiN) at the surface. Plasma nitriding was employed. However the high treatment temperature (900 C) may cause some component distortion. Boronising is a surface diffusion process also carried out at high temperature (800-1000 C) but in a pack medium. Boron diffuses into the surface to form a range of hard metallic borides. Eyre and Alsalim (Ref. 6) report improved wear resistance is obtained with boronised titanium alloys in pin on disc experiments. The surfaces were found to remain protected even after the boronised layer had been completely removed.

Thin, hard, ceramic layers of TiC, TiN, ZrN etc are increasingly used to protect metallic surfaces. Some examples include high speed drills, milling cutters, hobs and ball bearings (Ref. 7). Titanium alloy components have been satisfactorily coated wityh TiN (Ref. 8). Two processes were evaluated: sputter-deposited and arc-evaporated, the latter producing the thicker coating (0.5 and 4.5 microns respectively).

Table 2

Surface treatments examined

Treatment	Treatment Temperature (C)	Depth of Treatment (microns)	Coating Hardness (HV)
Tifran (oxidation)	650	5	600
Ion Plated Aluminium	180	2	350
Plasma Nitrided	900	2	> 400
Boronised	1000	5	~ 3000
Titanium Nitride	400	0.5/4.5	~ 3000

3. EXPERIMENTAL

3.1 Gear test rig

The ESTL gear test rig consists of a "four square" arrangement inside a vacuum chamber (Figure 1), with the pinion shaft being driven by an external motor via a rotary ferrofluidic feedthrough. The chamber is evacuated using a turbo molecular pump and ion pump.

The gear loading is applied by "winding-up" the torsional spring wire (positioned below the lower

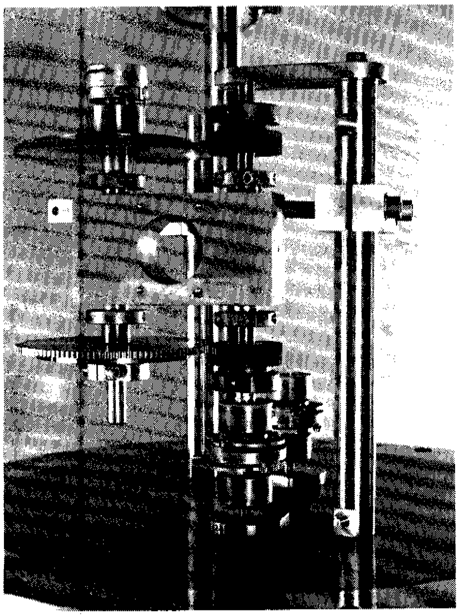


Figure 1. ESTL vacuum gear rig

wheel) to a specified torque before clamping the remaining gears to the shafts. The lower wheel is mounted on bearings and is free to rotate. The reactive torque, due to the frictional losses during gear mesh, causes the gear assembly to rotate backwards around the drive shaft. The motion is restrained by a load transducer at a fixed radius, the output from which is used to monitor the torque and hence indicate the efficiency of gear mesh.

3.2 Test-gears

The details of the ESTL gears are as follows:

Pinions 41 teeth, 0.75 mm module, 10 mm face width

Wheels 120 teeth, 0.75 mm module, 3 mm face width

The gears were manufactured to BS 978 Part 1 (1969) - Class C.

3.3 Test conditions

Pinion speed	150 RPM
Tooth load	7 and 14 N/mm (equivalent to maximum Hertzian contact pressures, p_o at the pitch point of 187 and 266 N/mm^2
Temperature	20 C
Vacuum	10^{-7} mbar

Each pinion was run unlubricated against a similarly treated wheel.

3.4 Assessment of gear performance

Three methods were used to assess the gear performance. These were:

(a) Effective life. From measurements of the gear torque and visual examination (via a chamber window), the effective life of the surface treatment was determined. The onset of surface treatment failure was indicated by a rise in gear torque to that found with untreated titanium gears. Visual observation confirmed the onset of galling on the gear teeth.

(b) Gear efficiency. The torque required to rotate the gears is equal to the frictional losses at the two gear contacts plus the frictional loss in the support bearings of the gear shafts. The torque of these bearings has been measured in a separate experiment. The gear torque figures have been corrected for the bearing losses. Therefore from the gear torque, the power loss or efficiency of gear mesh can be calculated from the equation:

$$\text{Power loss (\%)} = \frac{\text{Mean Torque x 100\%}}{\text{Tooth load x Pinion PCD}} \qquad (1)$$

(c) Wear depth. At regular intervals the depth of wear on the pinion gear was measured using a Talysurf 6 surface profilometer. This was performed without removing the gears from the shafts and hence without disturbing the contact conditions.

4. RESULTS

The effective life of surface-treated IMI 318 gears, at tooth loads of 7 and 14 N/mm is summarised in Figure 2. A preliminary test was performed with an untreated set of gears for comparative assessment.

The untreated gears began to adhere and gall within a few hundred pinion revolutions (or tooth encounters). Figure 3 shows the appearance of the untreated gears after 1 x 10^4 tooth encounters. Severe galling in the contact region is evident.

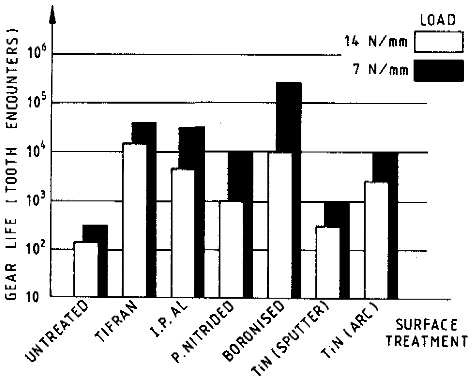
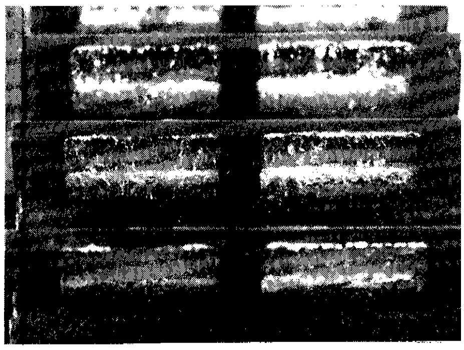


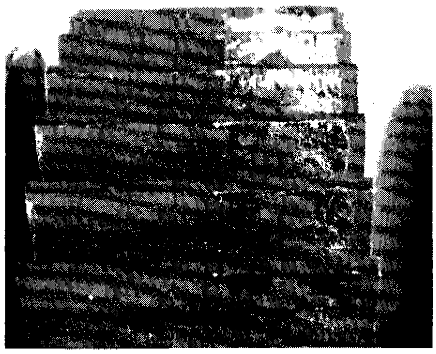
Figure 2. Effective life of surface-treated IMI 318 gears



x 10

Figure 3. Severe adhesive wear on untreated gear after 10^4 tooth encounters (loads 7 and 14 N/mm)

All treatments which were studied prolonged gear life; the best performance was obtained with the boronised treatment (with a life of 3 x 10^5 tooth encounters at a load of 7 N/mm). Illustrated in Figure 4 is the appearance of the boronised gear at the onset of adhesion. The treatment has initially been removed at the edges of the contact region. Further tooth encounters were found to cause adhesive wear and galling.



x 7

Figure 4. Onset of adhesion on boronised gear (3 x 10^5 tooth encounters)

The sputter-deposited titanium nitride coatings appeared to fail by lack of adhesion to the substrate rather than by coating wear. The arc-evaporated titanium nitride coating gave improved performance but failed due to surface break-up and concomitant adhesion between the softer substrates. The appearance of the arc-evaporated TiN at the onset of adhesion is shown in Figure 5.

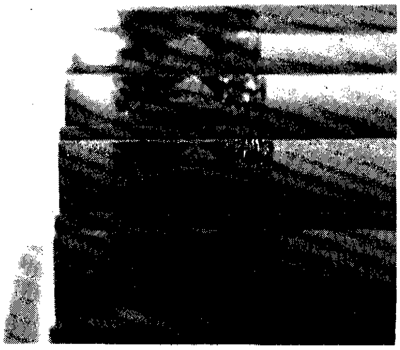


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Figure 5. Failure of arc-evaporated TiN coating

The frictional losses during gear mesh are summarised in Figure 6. The untreated gears had a power loss of 4%, which gradually rose as the number of tooth encounters increased. All treatments studied gave a frictional loss of between 2%-3% while the surface treatment was effective. Once worn or removed, frictional losses rose to that of the untreated gears.

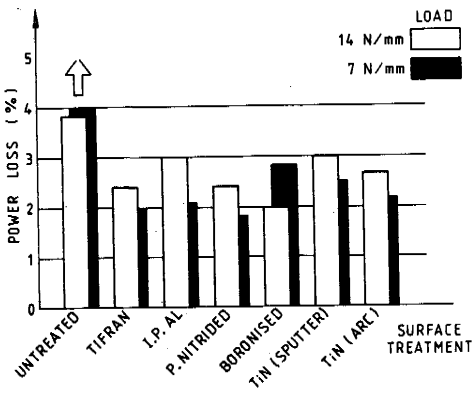

Figure 6. Gear efficiency

Measurements of the wear depths along the tooth flanks were found to be of limited value. While the surface treatment was effective, little wear was measured. In some tests the surface treatment had been entirely removed prior to the first measurement of wear depth. No measurable wear was found on the TiN coatings prior to coating removal. Once the treatments were removed and galling began then the wear depths measured were highly variable. Since galling would be intolerable in normal operation of gears in a satellite mechanism, treatment effective life is considered to be the relevant parameter.

5. DISCUSSION

This tribological study has indicated that surface-treated titanium gears can be employed for satellite applications, but, at present, only for a limited life. Comparison with identical tests on aluminium gears (Ref. 3) shows that titanium gears can give longer effective lives. Depending on treatment type, the life of the aluminium gears varied in the range 4×10^3 to 1.8×10^5 tooth encounters. For the same conditions, titanium alloy gears give lives in the range 1×10^3 to 3×10^5 tooth encounters. Both aluminium alloy and titanium alloy gears fail by severe adhesive wear. Boronised IMI 318 was found to give the longest gear life (3×10^5 tooth encounters). However dimensional checks, prior to and after treatment, showed that some growth had taken place (up to 1%). This resulted in an increase in the gear centre distance. In future applications allowance should be made during gear cutting for this dimensional change. The magnitude of this dimensional growth and small treatment depth (5 microns) could, however, limit the gear accuracy and precision achievable with this treatment.

Two factors contributed to the short lives obtained with the titanium nitride coatings. Firstly, lack of adhesion to the substrate. Measurements of coating adhesion using hardness indentations revealed spalling in the sputter-deposited treatment. Hence a long effective life was not expected. While it is beyond the scope of this paper to discuss factors which determine the adhesion of TiN to various surfaces, it is considered to be a matter of determining the optimum conditions and cleaning procedures for deposition rather than a fundamental limitation of the technique. Poor adhesion was responsible for the premature failure of the gear treated with sputter-deposited TiN.

Secondly, the deposition of hard, thin coatings on a soft substrate (similar to Bowden and Tabor's "mud on ice" analogy (Ref. 9)). Normally such coatings are applied to tough, hard substrates eg M 50 tool steel, which fully support thin hardened layers. In these trials, the emphasis was to use the TiN to avoid galling between the softer titanium substrates. The contact stresses were a factor of 10 below those required to cause plastic yielding in the titanium substrate. However under the frictional surface tractions, hard brittle coatings on soft underlying metal tend to fracture and become ploughed into the substrate. This mechanism occurs regardless of the adhesive qualities of the coating and hence determines the overall life of the coating on such substrates as titanium alloy. This mode of failure occurred with the arc-evaporated TiN coating.

The Tifran and nitrided IMI 318 gears failed by wear of the surface treatment. Metallographic examination revealed that all these treatments gave shallow depths of hardened surface layers. Thicker surface layers should improve gear life. For the ion-plated aluminium, the deposition conditions were such that little diffusion of aluminium into the substrate was achieved (Ref. 10).

These tests were performed unlubricated. The application of dry lubricants would considerably extend gear life and reduce frictional losses during gear mesh. To demonstrate this, an additional test was performed in which a 0.5

micron film of MoS_2 was sputter-deposited on a Tifran treated gear (surface roughness, Ra = 0.5 microns, tooth load 14 N/mm). This reduced the frictional losses to 1% and prolonged the life of the gears to 6 x 10^4 tooth encounters. No attempt was made to optimise the lubricant film in this test, rather it illustrates the improvement which can be obtained.

Based on these results, titanium nitride coatings on hard substrates show potential for gear satellite applications, provided that adherent coatings are obtained. They have the advantageous properties of corrosion protection, neglible wear and avoidance of gear distortion. Maraging gears treated with TiN are currently being evaluated at ESTL.

6. CONCLUSIONS

1. Of the treatments tested, boronised IMI 318 gears, gave the longest effective life when run, unlubricated, against a similarly treated gear in vacuum. However distortion, during treatment, limits the resulting gear precision.

2. Coatings of titanium nitride failed by lack of adhesion with the substrate and by mechanical fracture due to the soft underlying titanium substrate.

3. On removal of the surface treatment, by wear or otherwise, severe adhesive wear (galling) occurred with all gears.

4. Dry lubricant films extend the life of titanium alloy gears and reduce frictional losses during gear mesh.

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