Journal of the Korean Vacuum Science & Technology; JKVST
Vol.6, No.2, 2002, pp.62～66

Lifetime Enhancement of Aerospace Components Using a Dual Nitrogen Plasma Immersion Ion Implantation Process

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(Received)

Abstract

Hydraulic pumps are used to control the landing wheels of aircrafts, and their proper operation is vital to plane safety. It is well known that adhesive wear failure is a major cause of pump failure. A dual nitrogen plasma immersion ion implantation process calling for the implantation of nitrogen at two different energies and doses has been developed to enhance the surface properties of the disks in the pumps. The procedures meet the strict temperature requirement of <200℃, and after the treatment, the working lifetime of the pumps increases by more than a factor of two. This experimental protocol has been adopted by the hydraulic pump factory as a standard manufacturing procedure.

1. Introduction

Gaseous nitriding, a well-established technique for the surface modification of steels, has found many applications in the aerospace industry. One advantage of this technique is that the tribological properties of the treated samples can be enhanced without adversely modifying the bulk properties. Hydraulic pumps are used to control the landing gears of aircrafts, and the disks in these pumps are generally made of 25Cr3Mo steel and are the major cause of pump failure. It has been shown that the relatively short lifetime of aircraft hydraulic pumps manufactured in China is due to wear of the disks. In the past, using nitriding, the lifetime of the pump disks could be extended to several hundred hours, but the aerospace industry in China is demanding a better treatment method to further increase the wear resistance and lifetime of this critical component. The working environment of these pump disks is very harsh and unforgiving, and a soft material such as silver is often used as a wear couple. In addition, these disks which are lubricated by oil must be able to sustain a high continuous rotation velocity (about thousands of per minute) while being subjected to a heavy load in the field. As the major failure mechanism of the disks is adhesive wear, a number of methods such as the use of different substrate materials, thermal treatment, plasma nitriding, and coatings have hitherto been attempted to improve the wear-life of the disks, but the results have not been satisfactory from the commercial standpoint.

Recently, we used plasma immersion ion implantation (PIII) to treat the disks by taking advantage of the low treatment temperature, immersion characteristics, and cost-effectiveness of the technique [1-6]. The method can yield a hard nitrided zone thereby prolonging the lifetime of the pump disks. Our systematic investigation indicates that the best tribological properties can be attained by adopting a dual nitrogen PIII method. In the paper, the technical requirements, treatment procedures, experimental results, as well as diagnostic techniques are presented.

2. Technical Requirements

An example of a Z-5 hydraulic pump is depicted in Fig. 1. The surface requiring reinforcement has a diameter of 54 mm and is shown in the right picture. The total deformation and roughness allowances are strictly limited by the manufacturer to less than 1.8 μm and 0.15 μm, respectively. Moreover, deposition of cadmium coatings on the other side of the disks by electroplating is not viable due to incompatibility with subsequent processes. As PIII is the final step in the manufacturing process, a low treatment temperature is required to not negatively impact the bulk materials properties. In the factory, every treated disk must be inspected and pass the quality control test with respect to wear resistance and implant uniformity. The PIII retained dose must be properly calculated and easily adjusted by the operators. Hence, a simple and effective diagnostic method compatible with an industrial environment must be devised.

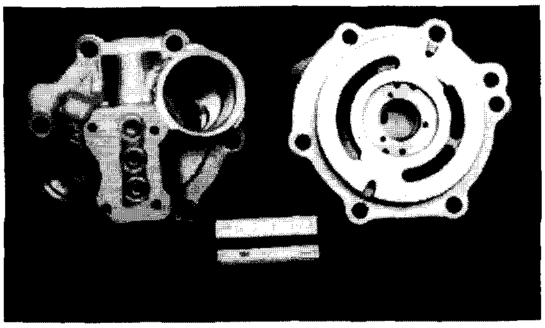

Fig. 1. A typical aircraft hydraulic pump disk treated by the dual nitrogen PIII process. The flat surface in the right picture is the critical area.

3. Experimental

In our preliminary experiments, planar specimens made of 25Cr3Mo nitrided steel with a diameter of 54 mm and thickness of 5 mm were implanted with nitrogen to determine the optimal parameters to yield a microhardness of about HV 800 at a load of 10 g and surface deformation of less than 1.2 μm in order to meet the hydraulic pump specifications. Before implantation, the samples were polished to a roughness R_a of 0.1 μm. Implantation was carried out in a multi-functional PIII instrument employing various implantation parameters and processing temperature [7,8]. In order to maintain the processing temperature below 200℃, a sample chuck was custom designed to accommodate the pump disks to permit enhanced physical contact for more efficient water cooling. Besides, a proprietary structure was implemented onto the upper side of the sample holder to attain more uniform implantation into the planar surfaces of the irregularly-shaped disks [9]. The pulse repetition rate was iteratively adjusted during implantation to control the sample temperature that was monitored using a special floating double thermocouple designed to minimize external interferences [10]. Vick's microhardness measurements were performed with a load of 10 g using a micromet tester, and the wear behavior was determined using a special MG-200 wear tester designed for very high speed rotation.

4. Results and Discussion

Our results indicate that the physical properties of the treated samples primarily depend on the processing temperature whereas the surface microhardness is more related to other implantation parameters such as implant energy and dose. At an implantation temperature of below 200℃, the changes in both the surface roughness and deformation are less than 20%, which is within the tolerance of the process.

Table I shows the microhardness measured from the various samples. It is clear that a dual nitrogen PIII process incorporating nitrogen implantation at a high energy after post implantation at a lower energy yields the best results. This is due to the high nitrogen concentration near the surface as shown in Fig. 2 resulting in nitride precipitation. Thus, a higher microhardness is achieved in spite of the relatively thin modified layer [11-13]. The multiple peaks in Fig. 2 arise from the co-implantation of different species in the hot-filament discharge plasma, primarily N^+ and N_2^+. Fig. 3 shows that the dual nitrogen PIII process yields the best wear resistance and friction properties as well. In our studies, a maximum microhardness is observed after dual nitrogen PIII assuming the substrate microhardness HV to be 800~950, and this corresponds to the saturated nitrogen retained dose in the substrate. It is also observed that the compressive stress is reduced. Based on our systematic studies, the optimal condition is a two step nitrogen PIII process: implantation voltage of 60 - 70 kV and implant dose of 1 - 6 × 10^{17} cm^{-2} followed by a second process of 30 - 45 kV and 1 - 4 × 10^{17} cm^{-2}.

The surface deformation and roughness results of the disks are exhibited in Figs. 4 and 5, respectively. The variation in the surface deformation is larger at higher implantation temperature whereas the change in the roughness is relatively smaller.

Table 1 Microhardness of samples measured at a load of 10 g [A: 65 kV, 3×10^{17} cm^{-2}; B: 30 kV, 1×10^{17} cm^{-2}].

Sample no.	Substrate microhardness (HV)	Treatment conditions	Microhardness increase (%) (compared with untreated sample)
1	743	A	11.7
2	740	B	7
3	755	A+B	19.2
4	804	A+B	26.3
5	847	A+B	20.7
6	926	A+B	10.7

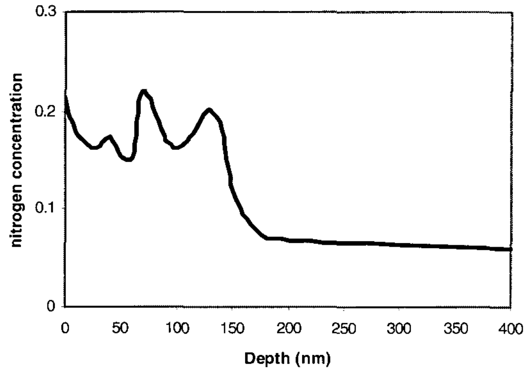

Fig. 2. Nitrogen elemental depth profile acquired by XPS from the sample treated by the dual nitrogen PIII process:
[65 kV, 3×10^{17} cm^{-2}] + [30 kV, 1×10^{17} cm^{-2}]

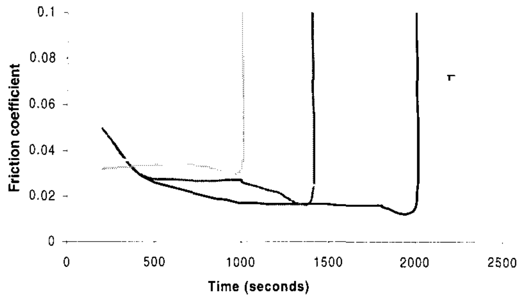

Fig. 3. Wear resistance (friction coefficient)data acquired from four samples treated under different conditions: (A) Untreated disk (control sample). (B) 30 kV, 1×10^{17} cm^{-2} nitrogen PIII. (C) 65 kV, 3×10^{17} cm^{-2} nitrogen PIII. (D) [65 kV, 3×10^{17} cm^{-2}] + [30 kV, 1×10^{17} cm^{-2}] nitrogen PIII.

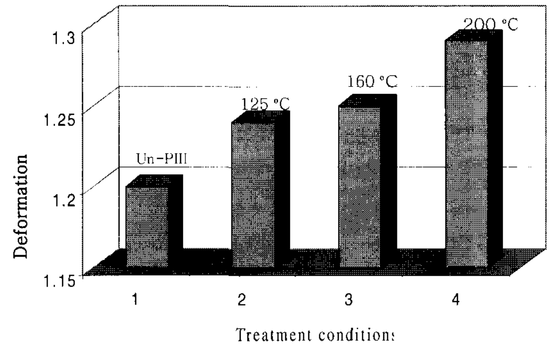

Fig. 4. Surface deformation results after [65 kV, 3×10^{17} cm^{-2}] + [30 kV, 1×10^{17} cm^{-2}] dual nitrogen PIII at different processing temperature. Disk1 is untreated and serves as the control.

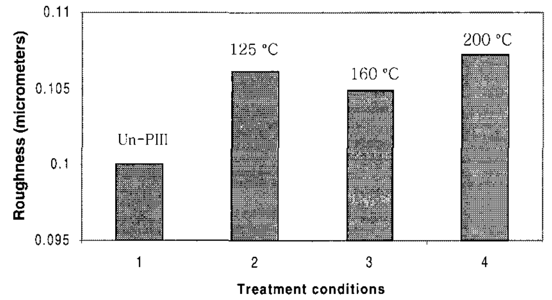

Fig. 5. Surface roughness data acquired from diskstreated by the [65 kV, 3×10^{17} cm^{-2}] + [30 kV, 1×10^{17} cm^{-2}] dual nitrogen PIII process at different processing temperature. Disk 1 is untreated and serves as the control.

After systematic studies and discussion with the production engineers in the factory, it is concluded that a surface deformation of below 1.5 μm and roughness of less than 0.12 μm before PIII treatment are acceptable, implying that the treatment temperature must be below 200℃. It should also be mentioned that the major cause of surface roughening in our process is due to sputtering which appears not to be very serious under the appropriate conditions.

The disks with and without the dual nitrogen PIII treatment were subsequently installed into the Z-5 hydraulic pumps. The pumps were then tested in a simulated operation using a 101-2 special tester for 100 hours. The conditions in the simulated runs are the same as those in real operation with the exception of the rotation velocity. The conditions were: oil pressure = 0.2 - 0.3 MPa in the inlet, rotation velocity = 4000 cycles/min and 6000 cycles/min. The oil leakage is an important criterion, and if the value is over 1.5 l/min, the pump will not operate properly. The disk wear resistance is substantially impacted by the oil outflow per minute. The results shown in Fig. 6 indicate that the value of the treated disk decreases to 1/16 of that of the untreated disk, thus unambiguously demonstrating a better wear resistance. Fig. 7 shows the results after operation in the field, further corroaborating the efficiency of the process. Our tests reveal that the lifetime of the pumps with the treated disks can be lengthened by more than a factor of two, e.g. from 120 hours to over 300 hours.

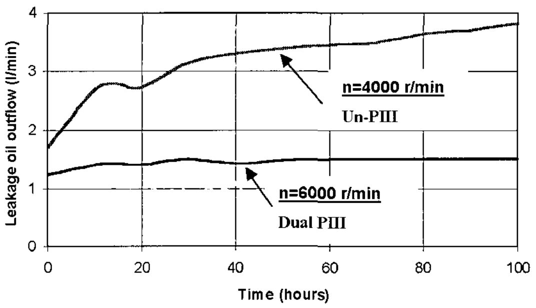

Fig. 6. Simulated oil leakage per minute versus operation time with and without the [65 kV, 3×10^{17} cm^{-2}] + [30 kV, 1×10^{17} cm^{-2}] dual nitrogen PIII treatment.

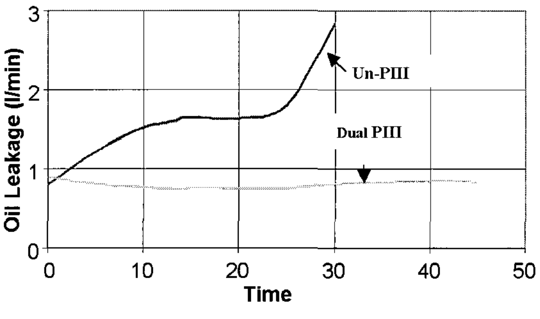

Fig. 7. Comparison of the oil leakage results from the untreated and dual PIII - treated disks based on field tests.

In an industrial environment, a direct and effective diagnostic method must be established to expedite and simplify the quality control process. After conducting lengthy trial studies together with the process engineers in the factory, a simple method has been developed. The process involves the visual inspection of the color uniformity on the treated disk surface and measurement of the incremental gain in the microhardness value. In order to pass the quality test, the disk surface must have a visually uniform light red color and the increase in the microhardness must be over 10%, while no surface damage can be detected. The dual nitrogen PIII and inspection processes described in this article were implemented into the production line of the company about a year ago, and every disk produced by the factory has been treated and inspected since then. The process has been demonstrated to be very reliable and the lifetime of the treated hydraulic pumps is currently over 300 hours reflecting a better than a factor of two improvement over the untreated ones. As a result, the process described in this paper is now a standard procedure of the company.

5. Conclusion

A substantial reduction in the wear and increase in the surface hardness have been achieved in 25Cr3Mo nitrided steels used in aircraft hydraulic pumps employing a special dual nitrogen plasma immersion ion implantation. The process consists of two steps: implanting nitrogen at 60 - 70 kV with a dose of $1 - 6 \times 10^{17}$ cm^{-2} followed by a second process at 30 - 45 kV and $1 - 4 \times 10^{17}$ cm^{-2}. The results from simulated and in-the-field tests demonstrate that the pump lifetime can be increased by more than a factor of two after the treatment. As a result, the methodology has been transferred to the Kuiyang Aviation Hydraulic Products Company in China and adopted as a standard production protocol for over one year.

Acknowledgements

The work was jointly supported by Hong Kong Research Grants Council CERG # 9040498 or CityU 1032/00E and City University of Hong Kong SRG #7001177.

References

[1] J. R. Conrad, J. L. Radtke, R. A. Dodd, F. J. Worzala, and N. C. Tran, J. Appl. Phys. **62**, 4591 (1987).

[2] J. Tendys, I. J. Donnelly, M. J. Kenny, and J. T. A. Pollock, Appl. Phys. Lett. **53**, 2143 (1988).

[3] P. K. Chu, S. Qin, C. Chan, N. W. Cheung, and L. A. Larson, Mat. Sci. Eng. Reports **17**, 207 (1996).

[4] S. Mandl, H. Reuther, J. Brutsher, R. Gunzel, and W. Moeller, Surf. Coat. Tech. **93**, 229 (1997).

[5] J. Pelletier, F. Le Coeur, Y. Arnal, A. Lacoste, and A. Straboni, Surf. Coat. Tech. **136**, 7 (2001).

[6] G. A. Collins, R. Hutchings, K. T. Short, and J. Tdendy, Surf. Coat. Tech. **103-104**, 212 (1998).

[7] Z. K. Shang, M. Geng, X. C. Zeng, K. J. Chen, H. H. Tong, et al., Surf. Coat. Tech. **85**, 105 (1995).

[8] Z. K. Shang, M. Geng, and H. H. Tong, China Nuclear Reports, CNIC-012004 (1997).

[9] H. H. Tong, Q. C. Chen, Y. F. Huo, K. Wang, T. M. Feng, L. L. Mu, J. Zhao, and P. K. Chu, submitted to Rev. Sci. Instrum.

[10] Q. Zhao, H. H. Tong, Q. Q. Chen, Y. F. Huo, M. Geng, and Y. Z. Chen, Nuclear Fusion and Plasma Phys. (in Chinese) **48**, 23 (2000).

[11] C. Blawert and B. L. Mordike, Surf. Coat. Tech. **93**, 274 (1997).

[12] C. Blawert, B. L. Mordike, U. Huchel, S. Stramke, G. A. Collins, K. T. Short, and J. Tendys, Surf. Coat. Tech. **98**, 1181 (1998).

[13] S. Y. Wang, P. K. Chu, B. Y. Tang, J. C. Yan, and X. C. Zeng, Surf. Coat. Tech. **98**, 897 (1998).