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Improvement of the wear and corrosion resistance of oil pump materials using plasma immersion ion implantation

S.Y. Wang [a,b], P.K. Chu [a,*], B.Y. Tang [a], J.C. Yan [b], X.C. Zeng [a]

[a] *Department of Physics and Materials Science, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong*
[b] *Harbin Institute of Technology, Harbin, PR China*

Abstract

A typical oil pump used in oil wells consists of a piston column, piston sleeve and ball valve. The working environment in an oil field is harsh and unforgiving, and the piston column in the oil pump is very vulnerable to wear and corrosion. Hence, improving the wear and corrosion resistance of the piston which is made of $45^{\#}$ steel is critical to the efficiency and profitability of oil companies. Even though ion implantation is an effective means to enhance the surface properties of the materials, the irregular shape and large dimension of the column make conventional beamline ion implantation very difficult. As the technique of plasma immersion ion implantation circumvents this line-of-sight restriction, it is a suitable technique to improve the wear and corrosion resistance of the components in an oil pump. A treatment process involving RF plasma nitriding and ion beam enhanced deposition (IBED) has been developed. The microhardness, mass loss due to wear, and coefficient of friction of the untreated and treated samples were measured. A salt fog test was also conducted to evaluate the resistance against rusting. The results indicate that the treatment improves the wear and corrosion resistance of the $45^{\#}$ steel samples significantly, and that the combined RF plasma nitriding and IBED process is more effective than a single RF plasma nitriding step. © 1998 Elsevier Science S.A.

Keywords: Plasma nitriding; IBED; Plasma immersion ion implantation

1. Introduction

Oil pumps are used in oil fields to extract crude oil from underground. A typical oil pump is composed of a piston column, a piston sleeve and a ball valve. Owing to the presence of dirty water, sand, soil, fat, weak acids and alkalis, as well as liquefied natural gas in an oil field, the oil pump must be able to tolerate harsh working conditions. In addition, the extraction pressure is quite high and can lead to accelerated breakdown of the components in the oil pump. Replacing a failed oil pump is non-trivial and may take up to 2 days as it can be located at a depth of 2000 m. Not only is it expensive to replace one (typical cost ~US$2500), but also the down-time contributes significantly to the operating cost. Hence, improvement of the wear and corrosion resistance of oil pumps, particularly the piston columns, is very important and is directly related to the profitability of the oil company. A typical piston column is made of $45^{\#}$ steel. Its length is 1.2 m, and the outside diameter is fixed at 44 mm, 56 mm, 70 mm, 83 mm or 95 mm. The manufacturing process of a piston column is quite complicated, and involves fine turning, Cr electroplating and fine grinding. The piston sleeve is made of $20^{\#}$ steel. Its length is 300 mm and its inside diameter is equal to the outside diameter of the corresponding piston column. Because of the rough field environment and the continuous rubbing action between the piston and the sleeve, the electroplated Cr layer can peel off or be scraped off easily, thereby exacerbating wear- and corrosion-related failures of the piston column and other components in the oil pump.

Ion implantation is frequently employed to enhance the surface properties of metal components, such as wear, corrosion and fatigue resistance [1]. However, because of the line-of-sight limitation inherent to conventional beamline implantation, target masking and complicated high-precision target manipulation are required to achieve reasonable dose uniformity for irregular and complex-shaped components. The resulting experimental complexity and high cost have thus hampered a wider acceptance of the technology in the oil industry. In contrast, the novel technique of plasma

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* Corresponding author. Tel: (852) 2788 7724; Fax: (852) 2788 7830; e-mail: appkchu@cityu.edu.hk

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immersion ion implantation (PIII) does not suffer from this line-of-sight restriction and overcomes the retained dose problem [2–10]. A comparison of conventional beamline ion implantation and PIII is shown in Fig. 1. PIII is therefore an excellent technique to treat complex-shaped and large industrial components such as oil pump columns. The objective of this work was to determine a treatment procedure for enhancing the wear and corrosion resistance and prolonging the lifetime of the piston and other components in an oil pump.

2. Experimental

The experiment was conducted using a custom-designed plasma immersion ion implanter [11]. The main stainless-steel vacuum chamber is cylindrical and measures 100 cm in diameter and 120 cm in height. A 13.56 MHz, 2 KW RF plasma source is positioned on top of the chamber to produce RF plasmas of high density and high purity. Four sets of MEVVA plasma sources are located around the chamber to introduce metallic ions into the plasma. Electrons emitted from four sets of multifilament electron guns are used to ignite the vacuum discharge plasma, and a set of RF antennae in the chamber enhances the radial and axial uniformity of the plasma. Sputtering deposition/coating can be performed in the same instrument by inserting a sputtering target and biasing it negatively while the sample is held at a ground potential.

The oil pump column is made of $45^{\#}$ steel and its chemical composition is listed in Table 1. This material is also often used in industrial components such as precision gears. Even though it is known that after ion beam treatment the materials can yield good mechanical strength and hardness, the process has not been studied systematically. Improving the wear and corrosion resistance of the piston columns of oil pumps and prolonging their working lifetime hinge on the success of increasing the thickness of the surface protection layer and decreasing the coefficient of friction. As the length of the column is 1.2 m and it is too big to fit into the chamber of our PIII equipment, planar $45^{\#}$ steel samples were prepared from it. The diameter of the samples is 30 mm and the thickness is 4 mm. These specimens are relatively easy to work with and measure, and the success of the treatment process can be readily assessed.

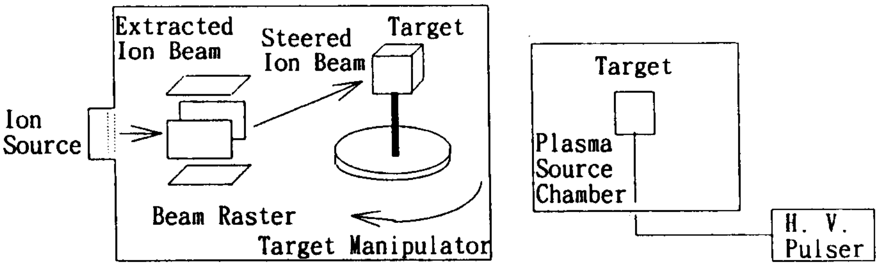
Table 1
Chemical composition of $45^{\#}$ steel

Element	C	Mn	Si	Cr	Ni
Composition (wt%)	0.42–0.50	0.50–0.80	0.17–0.37	0.25	0.25

Four $45^{\#}$ steel specimens were cut from an oil piston, lathed, polished, and chemically and ultrasonically cleaned prior to inserting into the instrument for PIII treatment. Sample 1 was untreated and became the control sample for comparison. Sample 2 was treated by RF plasma nitriding and the experimental parameters were: RF input power = 400 W, current = 8 A, implantation bias voltage = −30 kV, pulse frequency = 100 Hz, pulse width = 15 μs, nitrogen gas pressure = 6.75×10^{-3} Torr, implantation time = 1 h.

The processing conditions for sample 3 were similar to those for sample 2, with the exception that the implantation time was increased to 1.5 h. Sample 4 was treated using RF plasma nitriding coupled with ion beam enhanced deposition (IBED) using the following experimental sequence.

(1) RF plasma nitriding was performed first: RF input = 400 W, current = 8 A, implantation bias voltage = −10 kV, pulse repetition rate = 100 Hz, pulse width = 30 μs, working nitrogen gas



Beamline Implantation

(Line of sight process)

PIII

(Ions bombard all surfaces)

Fig. 1. Comparison between conventional beamline ion implantation and PIII. (**Left**) Conventional beamline ion implantation which is a line-of-sight process, whereas in PIII (**right**) ions are implanted into all surfaces of the target.

pressure $= 7.50 \times 10^{-3}$ Torr, and RF plasma nitriding time = 20 min.

(2) Sputter deposition was then conducted: Ti sputtering electrode voltage = −600 V, argon gas pressure $= 1.00 \times 10^{-2}$ Torr, and deposition time = 20 min.

(3) Nitrogen immersion ion implantation was performed last: nitrogen gas pressure $= 1.5 \times 10^{-4}$ Torr, filament current = 48 A, discharge bias voltage = 82 V, discharge current = 1.6 A, implantation bias voltage = −38 kV, pulse repetition rate = 50 Hz, pulse width = 15 μs, and implantation time = 1 h.

Coefficients of friction were measured using a simple experimental set-up. The steel ball was made of GCr15 with a diameter of 10 mm, hardness of HRC60 and roughness of ~0.05 μm (R_a). The testing velocity was ~1.4 cm min^{-1} and the applied load was 7.0 N. The microhardness of the four samples was measured with a load of 200 g. The mass loss due to wear was measured by a needle dish tester and a precision balance.

3. Results and discussion

In order to enhance the wear and corrosion resistance of the materials and prolong the lifespan of the oil column, the effective approach is to increase the surface hardness, form a superhard layer on the surface and decrease the surface friction. The RF plasma nitriding treatment using our new RF plasma source makes the implanted nitrogen ions diffuse further into the substrate and results in a thicker modified layer. Subsequent plasma deposition of Ti and nitrogen PIII form the superhard passivation film on the treated sample. The film not only improves the wear and corrosion resistance, but also decreases the coefficient of friction.

The microhardness of the four samples was measured and the results are depicted in Table 2. It can be seen that the longer RF plasma nitriding time led to a higher microhardness. Sample 4, which underwent a combined RF plasma nitriding and IBED treatment, possessed the best microhardness value. Conventional plasma nitriding of 1045 medium carbon steel (similar to 45# steel) has been investigated previously [12,13]. The reported microhardness of the treated samples is HV 250–400 (load 200 g), but the treatment temperature and time are ~450 °C and 20 h, or ~550 °C and 4 h. Compared with conventional plasma nitriding, our RF plasma nitriding process has several advantages, such as lower processing temperature (from room temperature to 150 °C) and shorter treatment time (1–2 h as opposed to 4–20 h).

Table 2
Microhardness of samples 1–4

Sample no.	Treatment technique	Microhardness HV	Microhardness improvement (compared with untreated sample) (%)
1	None	237	–
2	1 h RF plasma nitriding	283	19.4
3	1.5 h RF plasma nitriding	350	47.7
4	RF plasma nitriding and IBED	502	111.8

Table 3
Mass loss due to wear

Sample no.	Treatment technique	Mass loss (mg)
1	None	3.2
2	1 h RF plasma nitriding	2.2
3	1.5 h RF plasma nitriding	1.8
4	RF plasma nitriding and IBED	0.8

Table 4
Salt fog test results

Sample no.	Treatment technique	Test time	Rusted area
1	None	30 min	Seriously rusted
2	1 h RF plasma nitriding	5 h	~10%
3	1.5 h RF plasma nitriding	5 h	~8%
4	RF plasma nitriding and IBED	8 h	4%

The mass loss due to wear was measured by a needle dish tester and a precision balance. The measured mass losses after a 125.66 m wear route for the untreated and treated samples are displayed in Table 3. A trend similar to that shown in Table 2 can be observed. A longer RF plasma nitriding time yielded a smaller mass loss while sample 4 possessed the best property.

The salt fog test of the untreated and treated 45# steel samples was done by observing the rusted surface after a period of time, and the experimental results are listed in Table 4. The results confirm the data shown in Tables 2 and 3 and further illustrate the effectiveness of a longer RF plasma nitriding time as well as the superiority of the combined RF plasma nitriding/IBED sequence.

The coefficient of friction of sample 1 (untreated) and sample 4 (RF plasma nitriding plus IBED) was measured. The coefficient of friction of the untreated 45# steel samples was ~0.73 and ~0.33 for sample 4. The treated sample therefore had a lower surface friction.

4. Conclusions

The preliminary experimental results demonstrated that RF plasma nitriding as well as combined RF plasma nitriding and IBED are very effective in improving the wear and corrosion resistance of 45# steel samples. The microhardness, mass loss due to wear and rust resistance test results show that the treatment process combining RF plasma nitriding and IBED is the most effective. With the demonstrated success of these preliminary experiments, the next objective is to process the entire piston column. Since the length of the oil column is 1.2 m, which is too large to fit into the chamber of the PIII equipment, special quarter-length (300 mm) and half-length (600 mm) piston column samples will be made to evaluate the implantation dose uniformity along the surface. Finally, a chamber will be designed that is large enough to process real piston columns. It should be mentioned that other parts of oil pumps, such as piston sleeves, ball valves and stands, can also be treated using the techniques developed in this work.

In summary, since PIII circumvents the line-of-sight restriction inherent in conventional beamline implantation and overcomes the retained dose problem, it is an excellent technique to improve the wear and corrosion resistance of industrial components such as oil pump piston columns.

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