Efficiency of an SCM415 Alloy Surface Layer Implanted with Nitrogen Ions by Plasma Source Ion Implantation

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SCM415 alloy was implanted with nitrogen ions using plasma source ion implantation (PSII), at a dose range of 1×10^{17} to 6×10^{17} N^{+} cm^{-2}. Auger electron spectrometry (AES) was used to investigate the depth profile of the implanted layer. Friction and wear tests were carried out on a block-on-ring wear tester. Scanning electron microscopy (SEM) was used to observe the micro-morphology of the worn surface. The results revealed that after being implanted with nitrogen ions, the frictional coefficient of the surface layer decreased, and the wear resistance increased with the nitrogen dose. The tribological mechanism was mainly adhesive, and the adhesive wear tended to become weaker oxidative wear with the increase in the nitrogen dose. The effects were mainly attributed to the formation of a hard nitride precipitate and a supersaturated solid solution of nitrogen in the surface layer.

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1. Introduction

SCM415 alloy is widely used in many mechanical components since it has good mechanical properties, such as stiffness, and relatively economical efficiency. It is a common constituent in many industrial components, such as precision gear, shafts, pistons, and axles. Unfortunately, it is prone to wear because of its poor tribological properties and premature wear failure can occur in the field. A viable option is to improve the surface properties of SCM415 alloy using surface modification techniques without changing its bulk properties.

In recent years, nitrogen ion implantation has been successfully used to enhance the wear resistance by increasing surface hardening and reducing the coefficient of friction.[1] PSII is a promising technology for surface modification. It can enhance the surface properties of metals, polymers, ceramics, and semiconductors.[2-3]

Ion implantation is preferable for materials in which high-temperature surface treatment is undesirable. However, conventional ion implantation has its limitations: a low beam current results in a long implantation time; and beam scanning and target replacement are necessary for obtaining uniform implantation profiles in non-flat samples. Plasma source ion implantation (PSII) is a technique without these limitations that can provide equivalent material modifications.[4-6] The advantages of PSII over conventional ion implantation are its ability to treat large areas simultaneously and to implant non-planar targets without target manipulation and its low cost. PSII has no line-of-sight restriction or retained dose problem. This method has large commercial potential.[7-9]

This study investigated the nitrogen implantation of SCM415 alloy steel using PSII and described its tribological behavior. The nitrogen distribution profiles were measured using auger electron spectroscopy (AES) at various doses. The micro-morphology of the worn surface was observed using scanning electron microscopy (SEM). The weight loss, coefficient of friction, and micro-hardness were examined under different implantation conditions, and this study emphasized the tribological efficiency.

2. Experiment details

The chemical composition of SCM415 alloy steel is shown in Table 1. After carburizing and quenching treatment, specimens were fabricated in two shapes: ring specimens with dimensions of ∅60 mm × t16 mm and block specimens with dimensions of 12.7×12.7×12.7 mm^3. The end surfaces of all of the specimens were polished to a mirror-finishing grade of approximately 0.2 Ra. All the specimens were cleaned with acetone and alcohol in an ultrasonic cleaner before nitrogen ion implantation.

Table 1 The chemical composition (wt.%) of SCM415 alloy

C	Si	Mn	P	S	Cr	Mo	Cu	Ni
0.16	0.23	0.69	0.22	0.016	1.02	0.19	0.01	0.03

Table 2 PSII implantation conditions

Implantation parameters	Data
N_2 pressure ($\times 10^{-4}$ Torr)	1
Arc current (A)	0.5
Implantation voltage (kV)	60
Pulse frequency (Hz)	150
Pulse width (μs)	10
Implantation time (h)	1.5
Implantation dose ($\times 10^{17}$)	1.0; 3.0; 6.0

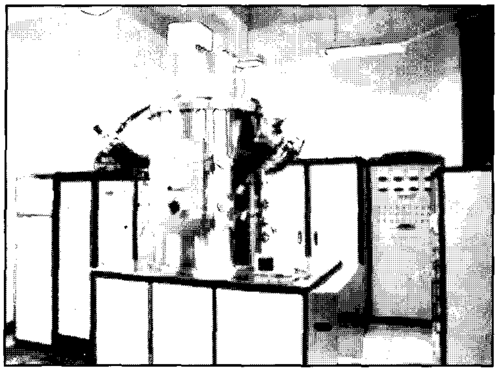


Fig. 1 The plasma source ion implantation device

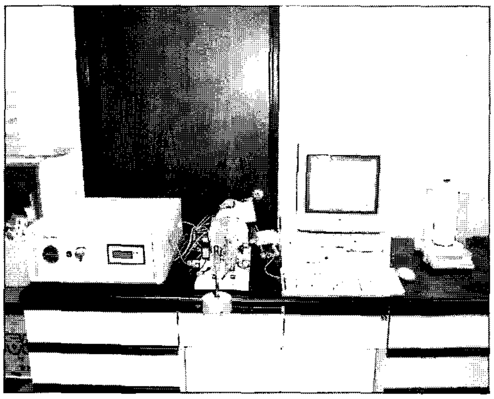


Fig. 2 Multi-purpose friction and wear tester

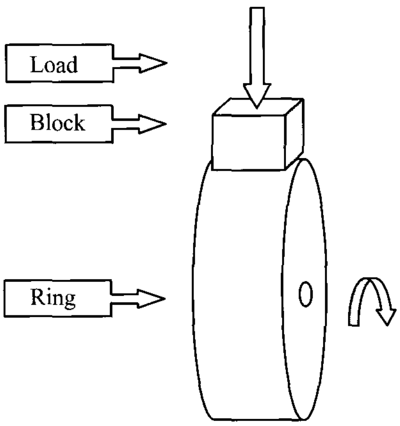


Fig. 3 Schematic illustration of the wear test

The experiments were carried out in a custom-designed plasma source ion implanter at the Korea Institute of Science and Technology. Its main vacuum chamber consisted of a stainless steel cylinder 100 cm in diameter and 150 cm in height. A 13.56 MHz, 2 kW RF plasma source was positioned on top of the chamber to produce an RF plasma with higher density and purity. Fig. 1 shows the PSII system, which consists of a vacuum chamber, vacuum pump, target table, magnetic filtering duct, cathode pole, gas intake, and bias voltage. The ion implanting energy was 60 kV, and the implantation doses were 1×10^{17}, 3×10^{17} and 6×10^{17} N^+ cm^{-2}. The implantation conditions are listed in Table 2. In order to clean the specimens, argon gas was forced into the chamber to sputter the surface of the specimens before nitrogen implantation, the gas flow was controlled at 5.0 cm^3/s, and the chamber pressure was about 2.0×10^{-3} Torr. This process lasted for twenty minutes. Then, the chamber was pumped down to below 1×10^{-4} Pa, and the nitrogen was forced into chamber under different the implantation conditions.

Block-on-ring wear tests were used to evaluate the friction and wear properties of the specimens using a plint-te53 multi-purpose friction and wear tester, as shown in Fig. 2. A schematic is shown in Fig. 3. The wear specimens were cleaned with acetone in an ultrasonic cleaner before and after each test. The specimens rotated at a speed of 500 rpm and a load of 67 N at room temperature, atmosphere pressure, and dry sliding conditions. The wear test lasted 2,000 seconds. Then, an electric balance was used to measure the weight loss of specimens.

The depth profiles were acquired using Auger electron spectroscopy (AES). An argon-ion beam was accelerated to 4 kV to sputter the samples incrementally, to determine the elemental depth distributions. After the wear test, the surfaces were inspected using SEM.

3. Results and Discussion

3.1 Analysis of nitrogen implantation layer

Fig. 4 shows the depth profile measured using AES. The samples were implanted with nitrogen ions at 60 kV, and doses of 1×1017, 3×1017, and 6×1017 N+ cm-2. The nitrogen content in the matrix had a Gaussian-like distribution with peaks at about 32, 25, and 22%, respectively. It is well known that the amount of nitrogen in low alloy steel is very small, about 0.005% in a solid at room temperature. Therefore, after ion implantation, not only is there a fine dispersion of Fe3N and Fe4N precipitates, but a supersaturated, dislocated solid solution of nitrogen also forms. These effects increased the surface hardness of the matrix.10-11. The solid solution of nitrogen is another mechanism strengthening the surface layer.

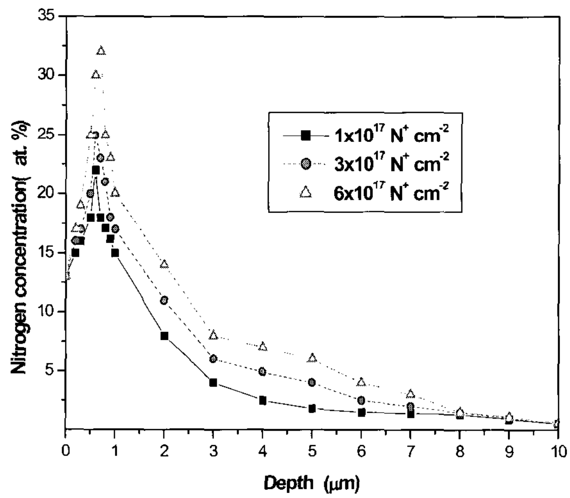


Fig. 4 The depth profiles of nitrogen in the ion implantation layer at various doses

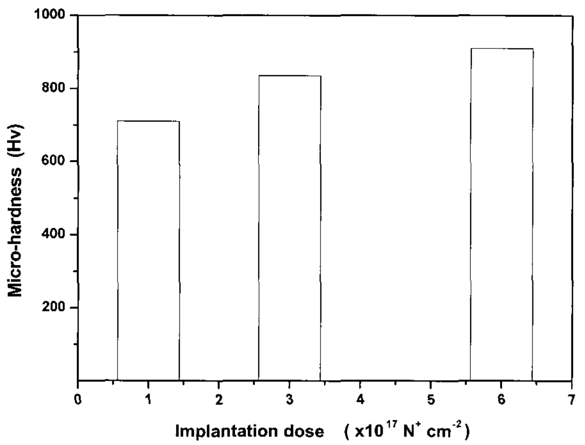


Fig. 5 The relationship between micro-hardness and various implantation doses

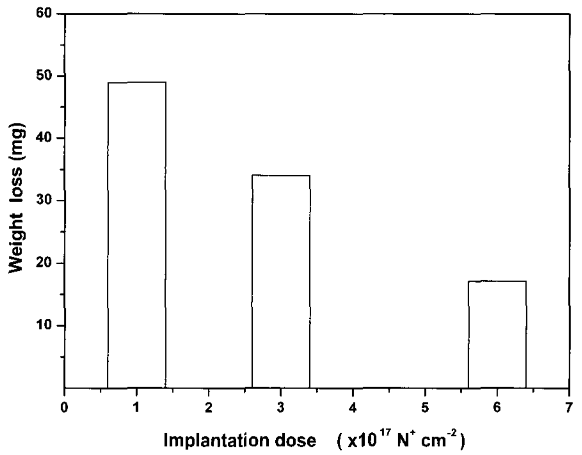


Fig. 6 The relationship between weight loss and various implantation doses

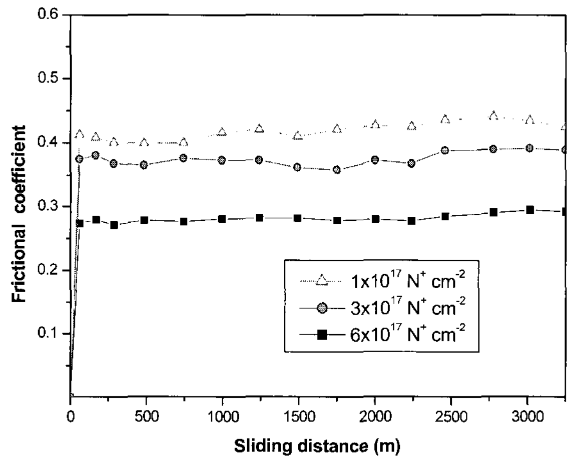


Fig. 7 The relationship between the surface frictional coefficient and sliding distance for various implantation doses

3.2 Micro-hardness test

Fig. 5 shows the micro-hardness data for nitrogen-implanted samples at various nitrogen doses. Each test was performed five times, and the average value was determined. Note that the micro-hardness increases with the nitrogen dose. When the nitrogen dose reached 6×10^{17} N^+ cm^{-2}, the micro-hardness was improved by about 30% over that at a 1×10^{17} N^+ cm^{-2} dose.

3.3 Weight loss test

Fig. 6 shows the relationship between weight loss and the nitrogen implantation dose under dry sliding conditions. The plotted data are the average of the results obtained from two tests at a load of 67 N. As this figure shows, the weight loss decreased with increasing nitrogen dose. At an implantation dose of 3×10^{17} N^+ cm^{-2}, the weight loss is about 30% lower than that at the 1×10^{17} N^+ cm^{-2} dose. When the nitrogen dose reaches 6×10^{17} N^+ cm^{-2}, the weight loss is reduced to approximately 60% of that of the 1×10^{17} N^+ cm^{-2} dose. This reveals that PSII improved the wear resistance of the surface layer. This can be attributed to the formation of Fe_3N and Fe_4N precipitates and a supersaturated solid solution of nitrogen during ion implantation. In general, the greater the micro-hardness, the smaller the measured weight loss is.

3.4 Frictional coefficient

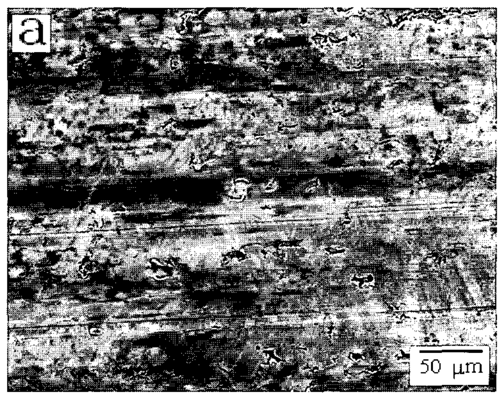
The relationship between the surface frictional coefficient and sliding distance for various implantation doses is given in Fig. 7. The average frictional coefficients are 0.412, 0.383, and 0.276, for the respective does. As this figure shows, the frictional coefficient decreased with increasing nitrogen dose.

Adhesive wear theory describes the frictional coefficient during the process of adhesive wear with following equation: [12]

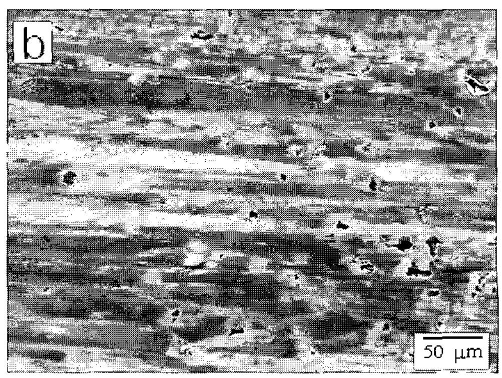
$$\mu=\tau/\sigma_s$$

where μ is the frictional coefficient, τ is the shear strength, and σ_s is the yield strength of friction contact surface.

After nitrogen implantation, (1) the surface layer was intensified increasing the yield strength, and (2) a second phase consisting of micro-grains of nitride had been precipitated, which damaged the continuity of the ferrite matrix. Therefore, the adhesive forces of the surface layer of SCM415 diminished, which means that τ decreased, reducing the frictional coefficients, while improving the wear resistance.



(a) $1\times10^{17}N^+$ cm^{-2}



(b) 3×10^{17} N^+ cm^{-2}

(c) 6×10^{17} N^+ cm^{-2}

Fig. 8 Micro-morphology of the worn surface observed using SEM: (a) 1×10^{17}, (b) 3×10^{17}, and (c) 6×10^{17} N^+ cm^{-2}

3.5 Wear test

The micro-morphology of the worn surface of SCM415 alloy observed using SEM (JEOL 5600) is shown in Fig. 8. Fig. 8(a) shows the worn surface after the wear test at an implantation dose of 1×10^{17} N^+ cm^{-2}. There are some micro-grooves in the direction of sliding and sheared dimples and craters, with some cracking in the worn scars. The plastic deformation indicates that metal has been removed. Increasing the implantation dose to 3×10^{17} N^+ cm^{-2}, there are also some sheared dimples and craters in the worn surface, but no cracking has occurred (Fig. 8(b)). Therefore, the adhesive wear tends to become weaker gradually. At a dose of 6×10^{17} N^+ cm^{-2}, as seen in Fig. 8(c), the wear track is smooth. There are only a few parallel tracks, and venial bruise traces in the worn surface. Therefore, oxidative wear appears to be the dominant wear mechanism. These findings reveal that after implanted with nitrogen ions, the tribological mechanism was adhesive wear. With increasing nitrogen dose, the adhesive wear tended to lessen. When the dose reached 6×10^{17} N^+ cm^{-2}, oxidative wear dominated in the tracks. This is why the weight loss and frictional coefficient were reduced. The effects were attributed to the formation of hard Fe_3N and Fe_4N precipitate and supersaturated solid solution of nitrogen in the surface layer. Therefore, the tribological characteristic was improved significantly.

4. Conclusions

1. After implantation with nitrogen ions using PSII, the distribution of the nitrogen dose has a Gaussian-like characteristic. The frictional coefficient of the SCM415 alloy surface layer decreases with increasing nitrogen dose.
2. The micro-hardness increases with the amount of nitrogen, while the weight loss decreases. The tribological behavior of the implanted surface layer had evidently improved. These effects are attributed to the formation of hard Fe_3N and Fe_4N precipitation and a supersaturated solid solution of nitrogen in the surface layer.
3. After implantation with nitrogen ions, the wear mechanism was adhesive; with increasing nitrogen dose, the adhesive wear tended to become weaker and oxidative wear dominated in the surface layer.

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