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Studies of N-ion-implanted stainless steels oriented for industrial applications

J.H. Lee, J.W. Park*, J.S. Lee, C.W. Sohn, J.K. Kil

Korea Atomic Energy Research Institute, P.O. Box 105, Yuseong-Gu, Daejeon-City, Republic of Korea

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Abstract

We have built an industrial 100-keV ion implanter for treating metal parts in order to increase wear resistance. 70-keV N ions of $>5\times10^{16}/cm^2$ were implanted into the surface polished stainless steel 420 (SS420) with average surface roughness (Ra) of 0.04 μm, and wear resistance of N-ion-implanted specimen at the mild abrasive condition was investigated. When the beam incidence was 45° with respect to the specimen surfaces, nitrogen was detected up to at least 300 nm from the surface, as measured with Auger electron spectroscopy (AES). X-ray photoelectron spectroscopy (XPS) analysis showed that the implanted N formed mostly Cr_2N without postirradiation annealing. Hardness profiles of the specimens were obtained with nanoindentation technique as a function of distance from the surface before and after ion implantations. The peak hardness of 14 Gpa formed at approximately 50-nm depth from the N-ion-implanted surface was about at least two times higher than nonirradiated specimen. Along with the hardness measurement, ball-on-disc wear resistance test was conducted with 500-gf alumina ball. The wear track to the onset point of abrupt increase in the frictional coefficient was about 5 m for the N-implanted specimen, while wear took place for the pristine sample as soon as the test started. On the other hand, when 1000-gf ball was used for the wear test, the difference in the wear track between the pristine and N implanted specimens was smaller than 500-gf ball. After the ion-beam irradiation, the surface roughness was reduced from Ra=0.04 μm to Ra=0.02, μm as measured with a high-resolution surface roughness tester. We found that the ion implantation prolonged the lifetime of the metal parts subjected to mild abrasive environment, like hair clipper blades.

Keywords: Ion implantation; Wear resistance; Auger depth profiling; Nitrides formation

1. Introduction

Coatings and ion implantation techniques are included in the major surface modification techniques to enhance the wear resistance of metal parts to abrasion [1,2]. Coated products have been known to have obvious advantages in the severe abrasive environments because the thickness of the coated layer is proportional to the coating time. In spite of sizable advances in the adhesion techniques between the coated layer and the substrate, the coated products often exhibit peeling problems during the service performance regardless of how mild the abrasive condition is. The abrupt interface that frequently formed in the coating products generates residual stresses in the coated layer, which cause the detachment of the coated layer from the substrate. For the metal parts to be used in a mild abrasive condition, sometimes the ion implantation is more useful than the coating because the implanted product does not produce an abrupt interface between the bulk and the treated layer. In general, the compressive residual stress generated in ion-implanted layer is not so significant as to peel the implanted layer off. However, ion-implanted surface is not suited to a severe abrasive condition because of limited treating depth which is a function of the ion energy [3].

Ion implantations in the elevated temperature and/or in the room temperature have been widely studied in recent years, and their effective application areas have been long pursued with varied implantation conditions. As found even in the up-to-date papers, the ion implantation into the

* Corresponding author. Tel.: +82 42 8682970; fax: +82 42 868 8131.
E-mail address: ex-pjw@kaeri.re.kr (J.W. Park).

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metal parts is worthwhile applying mainly to the parts that require for the wear—[4]and corrosion—resistances [5,6]. Because of the inconvenient sample manipulation with the conventional ion implantation process, recently, plasma source ion implantation (PSII) process has been widely developed [7–10].

In this paper, the characteristics of N-ion-implanted stainless steel by conventional ion implantation are reillustrated, and our experience in its industrial application is presented. This work was motivated by a company for the production of the prolonged lifetime of metal parts subjected to relatively mild abrasive environment. One of the examples for these applications is the hair clipper blade because the spring force to push the upper blade to lower blade is as low as about 500 gf, resulting in the stress of about 20 g/mm^2 on the surface of the blades. We have built a dedicated ion implanter for these applications and implanted N ions into stainless steel 420 (SS420) specimen. Then, mechanical tests, including nanoindentation and ball-on-disc wear tests, were conducted. In order to understand the surface-hardening mechanisms, Auger electron spectroscopy (AES) and X-ray photoelectron spectroscopy (XPS) were employed.

2. Experiments

An ion implanter with 50-KeV and 20-mA ion source and 50-keV accelerator tube was developed, aiming at commercial uses. For mass production of the implanted parts, higher density ion beam and larger irradiation area are required, and the irradiation area should be not only large but also uniform for the reliable mass production. In order to obtain more uniform irradiation area, we designed a beam extraction system with four holes aperture so that ion beams could be extracted from the ion source through four holes instead of a single hole [11]. Simulation with IGUN code [12] was followed to determine electrode materials and distances among the electrodes to obtain the required irradiation area. After building the implanter, SS420 plates were irradiated with N ions. Prior to ion-beam irradiation, 3×3-cm samples were polished to the surface roughness of 0.04 μm. Samples were placed in the area of 200×200 mm: one on the center and the others on the corners. Before the irradiation, the differences of ion doses during irradiation on the target were measured with a Faraday cage. The Faraday cage was designed to measure the ion beam current while passing the cage made of high-purity copper through the beam cross-section, presuming that the beam cross-section is circular. The current read in the X–Y recorder was converted to the ion dose by a proper calculation.

70-keV and 5-mA N ions were irradiated onto the specimens in a vacuum work chamber (base pressure=approximately 10^{-5} Pa and work pressure=approximately 10^{-4} Pa) for about 13 min, which is corresponding to about 5×10^{16} ions/cm^2 as we estimated with the Faraday cage measurement. That is, neutral atoms and molecules were not included in the dose estimation.

After irradiation, Auger electron spectroscopy (AES) depth profiling analysis was performed to see the existence of the nitrogen in the specimen and to obtain elemental profiles as a function of distance from the surface. A Physical Electronics Phi Model 670 Scanning Auger Multiprobe combined with an ion sputter gun was used for the elemental depth profiling. The Auger data were acquired $E\times N(E)$, however, the display mode of Auger spectra in this experiment is in $d\{E\times N(E)\}/dE$. The sputtering rate estimated in this work was about 10 nm/min.

Using Phi Model 5800 X-ray photoelectron spectroscopy (XPS) with an ion sputter gun, the chemical states of nitrogen residing in the subsurface of the implanted specimen were analyzed. The analysis was conducted after sputtering the surface until the surface contaminants such as C and O species were removed.

Nanoindentation and ball-on-disc wear resistance tests were performed on the implanted specimens. For ball-on-disc test, 1000-gf and 500-gf alumina balls were used, and the frictional coefficients were recorded as a function of wear distance. Although there are various ways of wear resistance test, in this work, the distance up to abrupt increase in the frictional coefficient was measured and compared with each other.

3. Experimental results and discussions

IGUN code simulation suggested that an additional 60-cm tube attached to 30-cm acceleration tube should produce a uniform irradiation area of 30 cm in diameter on the target.

As measured with a Faraday cage, consistent beam current of at least 5 mA was obtained at the beam energy of 70 keV on the surface of the target, and the difference of the ion doses between the center and the corners was about 10%, which is well consistent with the IGUN simulation results. At 70 keV and 5 mA, no distortion and dimensional changes of the specimens and the specimen holding jig system were observed. This means that the system can be used even without operating the target cooling system. After ion-beam irradiation, the surface roughness of the samples was reduced from 0.04 to 0.02 μm, as measured with a high-resolution surface roughness tester (Mitutoyo model Surftest SJ-301).

Fig. 1 shows Auger depth profiling results of the samples irradiated on the center and on the corners of the 200×200-mm specimens' holder. Fig. 1(a) denotes the sample positions in the holder, and Fig. 1(b) and (c) shows the examples of the Auger depth profiling. As can be seen in the depth profiling, the nitrogen is clearly incorporated in the N-ion-irradiated samples. As determined with software provided by Physical Electronics (USA), the concentration of nitrogen determined with peak-to-peak heights and atomic sensitivity factors was about 5 at.% at the near surface and