 Plasma immersion ion implantation (PIII) has been shown to be an effective surface treatment technique for industrial components, especially those possessing an irregular shape. Gears are widely used for rotary mechanical motion in various industrial machines. Extensive wear can occur on the surfaces due to mechanical contact but the complex shape renders conventional surface modification difficult. In this work, we investigated argon and nitrogen PIII of industrial gears. Rutherford backscattering spectrometry (RBS) was used to determine the implanted ion dose along the gear surface using silicon samples affixed at different positions. The results show that the lateral difference of implanted ion dose is quite large. We have also found a large iron content on the silicon surface at some positions. This corresponds to the degree of sputtering near this position and also reflects the ion implantation angle. Our results indicate that the ion dose along the tooth flank is less than that in other positions on the gear surface, and sputtering is more serious due to the larger ion incident angle as a result of the sheath propagation.

1. Introduction

Plasma immersion ion implantation (PIII) is a burgeoning technology for surface modification of materials [1–4]. Because there is no line-of-sight restriction, it is an excellent method to improve the surface properties of large and irregular-shaped industrial components [5–8]. In many machines, gears are used to transmit forces (or moments) between two unaligned shafts that generally rotate at different speeds. Much attention has been paid to ensure the long-term reliability of gears and to prevent gear damage, including using expensive materials, improving surface finishes, adopting new gear-cutting methods, introducing better surface treatment methods, and using high-performance lubricants [9,10]. The working surfaces of a gear are mainly its tooth flanks that come in contact with other teeth in operation. Carburizing or nitriding is the main workhorse in the industry to treat gears, but in some cases, additional surface treatment is needed to extend the working lifetime. It has been shown that PIII is an effective method to enhance surface hardness, improve wear resistance and decrease the friction coefficient [1–4,11,12]. Therefore, PIII may be an effective means to further improve the surface properties of industrial gears and extend the working lifetime.

Implant uniformity is an important factor affecting not only the efficacy of the treatment process but also the acceptance of PIII by industry. As a result, theoretical and experimental studies have been performed on specimens of various shapes [5–8,13–23]. Experimentally, Malik et al. [16] determined the implanted nitrogen concentration into a wedge-shaped target to study the spatial distribution of the implanted ions. Hartmann et al. [19] and Hochbauer et al. [20] investigated the PIII homogeneity on wedge-specimens (V- and D-shaped) with different angles. Mandl et al. [21] measured the PIII dose distribution on cylindrical samples such as drill bits possessing different diameters, and Ensinger et al. [22] and Ensinger and Volz [23] measured three-dimensional PIII dose uniformity on objects with trenches using thin film oxide as the probe. The results of these studies reveal that the PIII dose varies substantially with different target shapes. Most of these studies are based on the objects geometrically varying in rectangular coordi-
coordinates or \( r \)–\( \theta \)–\( z \) cylindrical coordinates with the symmetry in the \( \theta \) direction. In this work, we focus on the PIII treatment of an industrial gear that geometrically varies in the \( r \)–\( \theta \) cylindrical coordinates. Nitrogen PIII was conducted on the gear surface and the implant uniformity along the gear surface was investigated. We also studied the severity of sputtering using Ar PIII and oxygen contamination along the gear surface.

2. Experimental

An industrial spur gear (shown in Fig. 1) with diametrical pitch \( DP = 1/5 \) and tooth number \( Z = 18 \) was studied in our experiments. It is made of #45 carbon steel (composition in wt.\%: C 0.42–0.5% Si 0.17–0.37% Mn 0.5–0.8% Ni 0.25% Cr 0.25% Cu 0.25% S 0.035% P 0.035%, and the rest Fe). As shown in Fig. 1, the outside diameter of this gear is 100 mm and the inside diameter is 78.43 mm. The thickness in height direction is 40 mm. To study the implant dose variation along the gear surface, pieces of silicon \((2/3 \times 3 \, \text{mm})\) were affixed using conductive silver paint onto the tooth surfaces, as shown in Fig. 2. The experiments were carried out in a multipurpose plasma immersion ion implanter [24]. The gear was placed horizontally on a 2-mm-thick steel platen having the diameter of 50 mm. The platen was connected to the sample stage in the vacuum chamber by a steel rod 6 mm in diameter and 400-mm long to establish support and electrical contact. The placement of samples E1–E3 on the bottom (lower side) was similar to that of samples A1–A3 on the top (upper side). Before the experiments, the vacuum chamber was pumped down to a base pressure of \( 8 \times 10^{-4} \) Pa. Then, nitrogen or argon gas was introduced into the chamber, and the plasma was ignited by a hot filament glow discharge. Normally, without intentional sample cooling or heating, the implantation temperature during PIII is below 200 °C. The experimental conditions are summarized in Table 1. The same experimental conditions were used for nitrogen and argon PIII processing. After PIII, the silicon samples were analyzed using Rutherford Backscattering Spectrometry (RBS) to acquire the implanted layer information and calculate the implant dose at various locations along the gear surface. RBS analysis was performed with a 2-MeV He ion beam and detection angle of 170°. The focus of our experiments is on the variation of the retained doses along the gear surfaces, and so we did not measure the nominal implant dose, but based on experiments done under similar conditions, it is estimated to be about \( 3 \times 10^{17} \text{ cm}^{-2} \).

3. Results and discussion

Fig. 3 shows the RBS spectra acquired from samples C1 to C5 treated by argon PIII and indicates the existence of three elements (Ar, Fe and O) on the surface of the silicon samples. During argon PIII, Fe is sputtered from the gear surface around the silicon sample and re-deposited onto the surface of this sample. Hence, the Fe content is a good measure of the degree of sputtering occurring in the vicinity of the sample. We note that there is a high oxygen peak in some silicon samples. It can be attributed to residual oxygen and water vapor in our PIII chamber as well as out-gassing, especially when hot filament glow discharge is employed to ignite the plasma. Based on the spectra, the Ar, Fe and O contents are different at different locations along the tooth surface. At the tooth top (sample C1), the Ar peak is higher

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Experimental conditions of argon and nitrogen PIII processing</th>
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<tr>
<td>Target bias (kV)</td>
<td>Pulse width (us)</td>
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and no Fe is detected. Along the tooth flank (samples C2 to C4), the Ar and O peaks become smaller, but the Fe peak is larger. At the bottom of the tooth gap (sample C5), the Ar and O peaks increase again, and Fe content decreases.

Fig. 4 depicts the distribution of the Ar and N retained dose of samples C1 to C5 treated by argon and nitrogen PIII, respectively. It can be observed that the implanted dose distributions along the tooth surface are almost the same for nitrogen and argon PIII. The implanted doses at the tooth top (sample C1) and the gap bottom (sample C5) are higher. The retained dose becomes gradually lower from the tooth top to the tooth bottom (samples C2 to C4). The dose difference along the tooth flank is 2.4 times for argon PIII and 2 times for nitrogen PIII, respectively (samples C2 to C4). The lateral dose uniformity is therefore not very good along the tooth flank. Moreover, comparing the absolute value of the dose, the nitrogen retained dose is much larger than the argon dose under the same PIII conditions. The argon mass is larger than that of nitrogen, and so the projected range of Ar is smaller and sputtering effects are much more serious for Ar ions at the same implant energy and incident angle. It is thus reasonable that the Ar retained dose is smaller than that of nitrogen.

Fig. 5 exhibits the argon retained dose distributions on the gear surface at different positions. It can be observed...
that the distributions of Ar are almost the same for the upper (B), middle (C) and lower (D) positions at different heights. The tooth top (position B1, C1, D1) has a larger Ar retained dose and the tooth flank and the location close to the tooth root (position B4, C4, D4) have the lowest doses. Fig. 5 also shows the Ar retained doses of samples affixed on the gear top (samples A1–A3) and bottom (samples E1–E3). The Ar dose implanted into the gear top is higher than that at the bottom. It can be attributed to that the ions near the gear bottom are still affected by the supporting platen and rod. During PIII, ions around the gear bottom can be implanted not only into the gear surface but also into the platen and rod, and so the number of ions implanted into the gear bottom surface may be lower than that into the top surface.

Fig. 6 displays the oxygen content distribution of the samples affixed on the tooth surface. Comparing Figs. 5 and 6, the trend of the Ar and O variation along the tooth surface is almost the same. Residual oxygen or water vapor may also be ionized and implanted into the target during PIII. Although the mechanism of oxygen introduced into the target surface is not only via ion implantation because we have observed that the oxygen depth profile does not exhibit a Gauss distribution in many PIII experiments [11,12,25,26], the concentration on the surface is the highest and decreases with the depth. Therefore, it is believed that surface oxygen incorporation is mainly by implantation together with relatively minor surface absorption and plasma oxidation.

Fig. 7 displays the distribution of Fe in samples affixed on the gear surface. On the tooth top (positions B1, C1, D1), no Fe can be detected. The Fe concentrations increase from the tooth top to the tooth root (samples B2 to B4, C2 to C4, D2 to D4). Iron is also detected on samples B5, C5, D5 affixed at the bottom of tooth gap. Moreover, no Fe is detected from samples A1 to A3 and little Fe is found in samples E1 to E2. Because Fe atoms are sputtered from the gear surface and then re-deposited on the silicon samples, the iron content can reflect the degree of sputtering near the sample position. Our results indicate that sputtering is very small on the tooth top, and becomes progressively more substantial further down.

Our results show that degree of sputtering is different at different positions along the tooth surface. The samples with a large argon retained dose have low Fe contents, and vice versa. Sputtering depends on three primary factors: ion species, ion energy and incident angle. During the PIII experiment, the ions are the same for different target positions, and the ion energies are almost identical except during the beginning or rise time of the high voltage pulse. Hence, the various degrees of sputtering at different positions are mainly due to the different ion incident angle. When the bombarding ion is incident at a glancing angle $\theta$, the sputtering yield $Y(\theta)$ is larger than the normal incidence yield $Y(0)$. The angular sputtering yield $Y(\theta)$ has the following relationship [4]:

$$Y(\theta) = Y(0)(\cos\theta)^{-f_s},$$

where $\theta$ is incident angle from the surface normal and the exponent $f_s$ is approximately 2. The incident angle depends on the ion trajectory. When a pulse is applied to the gear, an ion-matrix sheath is subsequently formed around it. Ions are accelerated by the sheath electric field and
implanted into the gear surface. In the beginning of the bias pulse, only the ions close to the target are accelerated and the ion sheath is geometrically conformal with the gear surface. The ions impinge into the gear surface almost perpendicularly ($\theta = 0$). However, as the sheath expands, the sheath becomes more spherical and non-conformal with the target as shown in Fig. 8. The ions are accelerated from the sheath edge and obtain very high velocity. These ions follow the radial ion trajectories as shown in Fig. 8 because of their inertia. Therefore, on the tooth top, the ions impact the surface perpendicularly even after the sheath has propagated a large distance from the gear surface. In contrast, the ions impinge into the tooth flank at a more glancing angle resulting in a higher degree of sputtering. The incident angles along the tooth flank become larger gradually from the tooth top to the tooth root (corresponding to samples C2 to C4), as confirmed by that the detected Fe contents increase from sample C2 to C4. Fig. 8 shows that the ions bombard the bottom of the tooth gap perpendicularly, but some Fe contents are still detected at the bottom of tooth gap (samples B5, C5 and D5), and it indicates large sputtering at the gap bottom positions. Similar results have been observed by Ensinger et al. [22] and Ensinger and Volz [23] in PIII of the three-dimensional trenches. They also found severe sputtering in the trench bottom. Fig. 8 only shows the two-dimensional $r-\theta$ plane case. Because the tooth gap (also a trench) has side openings in the height direction, ions can also enter the tooth gap from the upper and lower sides in the axial direction. These ions are also accelerated from a spherical sheath and bombard the bottom of tooth gap at a glancing angle. Therefore, sputtering occurs at the bottom positions of tooth gap. The retained dose of ion implantation decreases with the incident angle, and the relationship is given by

$$D = \Gamma \cos \theta$$

(2)

where $D$ is retained dose, $\Gamma$ is incident ion dose and $\theta$ is incident angle. So the retained dose distributions along the total gear surface are inversely proportional to the variation of sputtering and the ion incident angle.

4. Conclusion

An industrial spur gear was treated by argon and nitrogen plasma immersion ion implantation to study the efficacy of PIII into such a structure and the ion dose uniformity along the tooth surface. The lateral uniformity along the gear flank (main working surface) is not very good, and the maximum dose difference along the gear flank can be as high as 2.4 times for argon PIII and 2 times for nitrogen PIII. On the surface of the tooth flank, the retained dose decreases gradually from the tooth top to the tooth root. The iron contents detected from the silicon samples can reflect the degree of sputtering at different positions. The degree of sputtering at different positions is related to the ion incident angle at these positions. Therefore, this method can be used to detect not only the uniformity of the ion dose but also the degree of sputtering and the variation in the ion incident angle.

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References