Preliminary investigation into the load bearing capacity of ion beam surface modified UHMWPE

W. SHI*
School of Materials and Engineering, Shanghai University, Shanghai 200072, People's Republic of China
E-mail: wenshi28@hotmail.com

X. Y. LI, H. DONG
Department of Metallurgy & Materials, School of Engineering, University of Birmingham, UK

Ion beam surface modification has attracted much attention and achieved some success in the surface engineering of polyethylene [1, 2]. For example, nitrogen ion implantation of ultrahigh-molecular-weight polyethylene (UHMWPE) has been proved to improve its surface hardness and tribological properties [2]. However, with this technique, it is difficult in practice to uniformly treat three-dimensional objects such as acetabular cup in artificial hip joints without using sophisticated manipulating devices. Plasma immersion ion implantation (PIII) is a new surface modification technique that offers substantially uniform surface modification of components owing to the ease of the line-of-sight restriction of conventional ion implantation (CII) [3]. Although the surface chemistry [4] and tribological behavior [5] of ion beam modified UHMWPE have been evaluated, no attention has been paid to the load bearing capacity (LBC) of PIII-modified UHMWPE. In the present investigation, an attempt has been made to compare the LBC of CII- and PIII-treated UHMWPE using nanoindentation and cross-sectional TEM and EDX.

Medical grade UHMWPE (GUR 4150 HP) was machined from bar stock material into discs of 5 mm in thickness and 12 mm in diameter. Then, the disc surfaces to be treated were ground and polished to an average surface roughness value (R_a) of about 0.02 μm. The UHMWPE discs were surface modified by CII and PIII with nitrogen. The CII treatment was carried out at a pressure of about 10^{-3} Pa at 80 kV to a dose of 1×10^{17} ions cm^{-2}. The PIII treatment was undertaken using a Mark 1 PIII system at a pressure of 1.7×10^{-3} mbr (1.3×10^{-5} Pa) to a dose of 1×10^{17} ions cm^{-2}. The LBCs of the as-received and the ion beam surface modified UHMWPE were studied by measuring the surface nano hardness with gradually increasing the penetration depth from 250 to 2000 nm by using a NanoTest 600 machine with a Berkovich diamond indenter.

It can be seen from Fig. 1 that surface hardening has been achieved by both the CII and the PIII treatments, and that the surface hardness for both implanted and the untreated UHMWPE is a function of the penetration depth of the indenter. The CII-treated sample showed a higher hardness than the PIII-treated sample when penetrated to depths up to 500 nm. When indented to a depth ≥1000 nm under a high load, while the hardness of the CII sample reverted to the value of the untreated material (50 MPa), the hardness of the PIII sample (70 MPa) was still higher than that of the untreated material. Clearly, the PIII-treated material possesses a higher LBC than the CII treated one, especially when indented to a deep depth or under a high load. It is thus speculated that the depth of the surface-modified layer may be larger for the PIII-treated than for the CII-treated material. However, TRIM calculation revealed that the range of the implanted nitrogen ions or the depth of the modified layer in UHMWPE for the CII (80 keV) and PIII (at 20 keV) treated material is about 350 and 120 nm, respectively.

Clearly, the difference in the LBC of the CII-and PIII-treated UHMWPE (see Fig. 1) cannot be explained based on the depth estimated from the TRIM simulation. It thus implies that the TRIM method may not be applicable to the PIII-treated polymers and direct experimental measurements are needed to clarify the issue.

To this end, cross-sectional transmission electron microscopy (XTEM) of the ion beam surface modified UHMWPE was carried out. The XTEM specimens were ultra microtomed by a diamond knife into 65-nm-thick cross-sectional slices and examined at an operating voltage of 200 kV using a Jeol 4000FX STEM. A high-resolution 200 keV FE TEM, TechNine, equipped

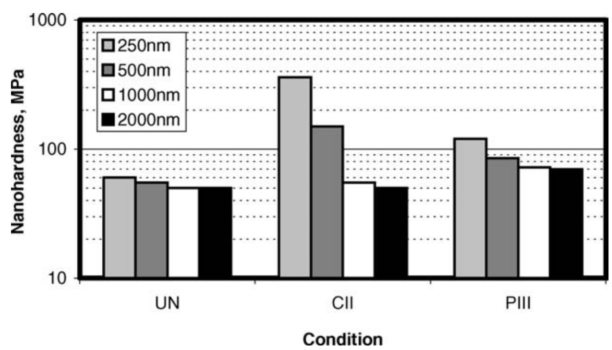

Figure 1 The load bearing capacity of ion implanted (CII), plasma immersion ion implanted (PIII), and untreated (UN) UHMWPE.

*Author to whom all correspondence should be addressed.

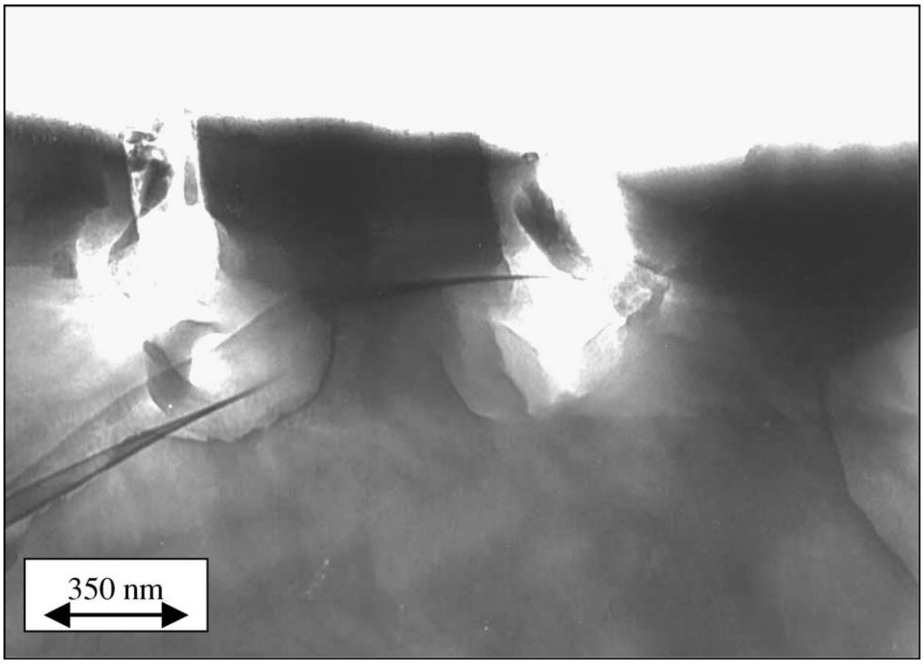

Figure 2 A bright-field cross-sectional TEM image of the microstructure of the CII specimen showing the approximately 350-nm-thick modified layer in darker contrast as well as some cracks.

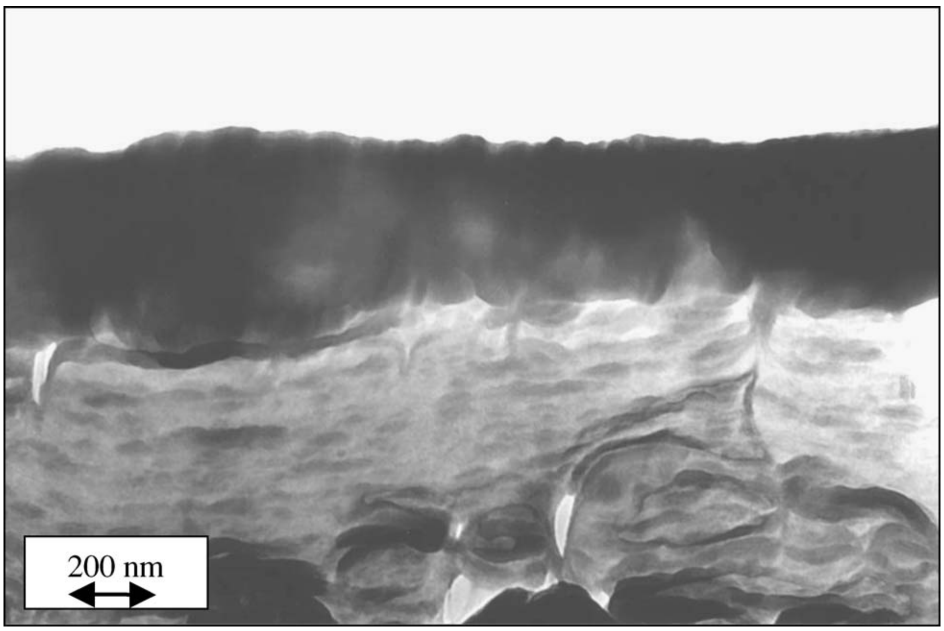

Figure 3 A bright-field cross-sectional TEM image of the microstructure of the PIII specimen showing the approximately 400-nm-thick modified layer in darker contrast.

with an EDX facility, was employed to directly measure the nitrogen distribution.

Fig. 2 shows a representative bright field image of the cross section of the CII-treated specimen. It can be seen that the implanted layer appears darker than the substrate and was partially broken owing to its brittle nature. The average thickness identified according to the darker contrast relative to the substrate was approximately 350 ± 15 nm, which is in good agreement with the TRIM simulation value (350 nm). Therefore, the dark contrast along the edge of the sample (Fig. 2) was most likely caused by the nitrogen ion implantation. A typical bright field XTEM image of the PIII specimen is shown in Fig. 3 and the thickness of the surface modified layer identified according to the darker contrast is approximately 400 ± 20 nm, which is more than three times that of the TRIM simulation value.

It is believed that the dark surface layer observed in the XTEM ion beam surface modified samples was most probably caused by mass effect arising from the introduction of nitrogen ions since mass contrast is the critical contrast mechanism for most amorphous polymeric materials. Regions of higher density will scatter more and hence appear darker [6]. Accompanying the introduction of nitrogen ions, the mass or density of the implanted layer becomes larger relative to the substrate.

The nitrogen depth distribution was directly measured using the EDX of high-resolution FETEM and

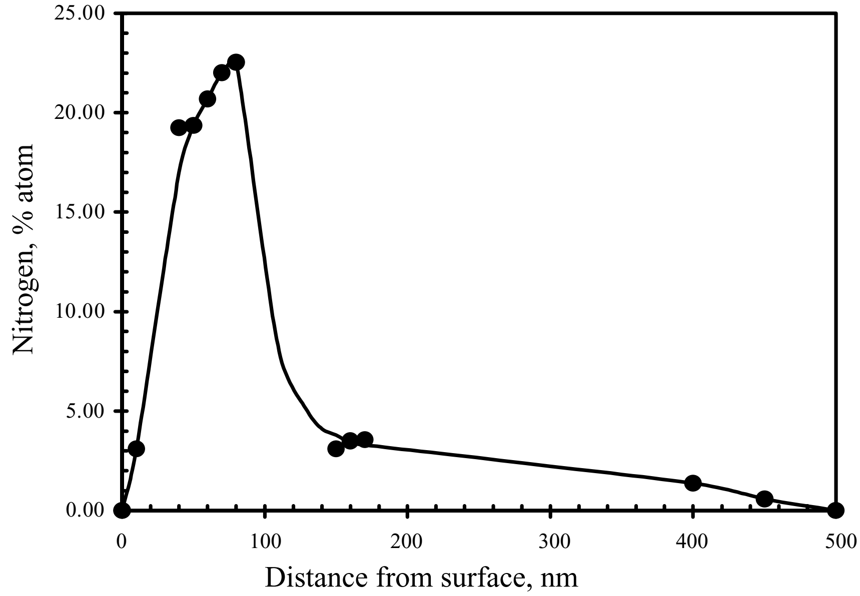

Figure 4 A nitrogen depth profile of the PIII specimen revealed by high-resolution XTEM coupled with EDX analysis.

it was found that the nitrogen peak is approximately 90 nm below the surface (Fig. 4). The measured curve (Fig. 4) is highly asymmetric with a long tail until a depth of about 400 nm. The experimentally measured depth (400 nm) is much larger than the ion range (120 nm) calculated from the TRIM program but in good agreement with the value measured from the dark surface layer by XTEM.

Therefore, the superior LBC at a penetration depth of 2000 nm for the PIII-treated sample could be partially attributed to the deeper modified layer (400 nm) than that given by the TRIM simulation. It thus implies that different mechanisms may be involved. The deep modified layer could be partially attributed to the pulse source used in the PIII. Unlike in conventional ion implantation, the implantation of nitrogen ion during PIII treatment occurs intermittently and the implantation period is only about 0.6% of a whole voltage cycle (10 ms) (Fig. 5). Therefore, ions implanted by PIII are expected to move deeper due to smaller hindrance arising from collision between scattered ions and recoiled atoms with moving ions following "ion implantation (bias pulse on) and little hindrance during ion diffusion" (bias pulse off) [7].

However, it is also noted from Fig. 4 that although the thickness of the whole modified layer was about 400 nm, the nitrogen tail beyond the first 100 nm is very low. Therefore, the hardening effect alone could not fully account for the higher LBC at a penetration depth of 2000 nm for the PIII sample than for the CII-treated sample. It is thus advisable to note that LBC depends both on the surface hardness and on other surface mechanical properties. Although high-energy (80 kV) ion implantation could effectively harden UHMWPE, the high fluence ion implanted layer was embrittled to some extent, as evidenced by the occurrence of the kink on the nanohardness loading curves [8]. Therefore, the low LBC of the CII-treated sample could be partially attributed to the embrittlement of the implanted layer.

As schematically shown in Fig. 6, the surface modified layer could provide effective resistance to the impression of an indenter provided the surface modified layer can comply with the deformation of the substrate without rupture. Therefore, a hard and tough modified layer can partially support the applied load even if the maximum penetration well exceeds its thickness (Fig. 6a). This is the case for the PIII-treated UHMWPE: although the maximum penetration depth was reached in 2000 nm, which is about five times the

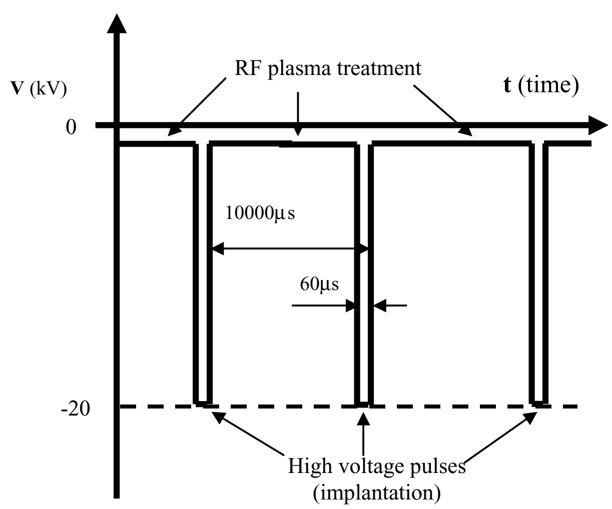

Figure 5 Variations in workpiece potential during PIII treatment.

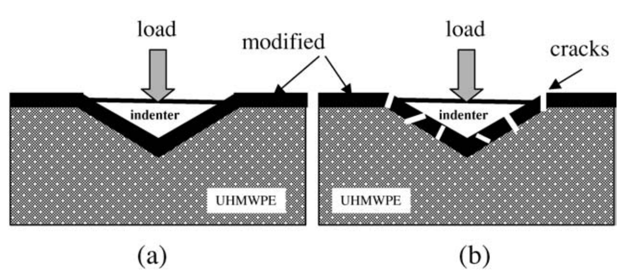

Figure 6 Schematic of the indentation behavior of (a) strong and tough layer and (b) hard but brittle ion beam modified layers on soft UHMWPR.

thickness of the PIII surface modified layer, the measured surface hardness is still higher than that for the substrate. On the other hand, high fluence ion implanted UHMWPE is hard but brittle. Such a surface modified layer may provide some support to the applied load within the critical deformation limit. However, when indented to a large depth, this modified layer would not provide any resistance to the applied load if it were broken (Fig. 6b).

In summary, when indented to a deep depth or under a high load the plasma immersion ion implanted UHMWPE possesses a higher LBC than the conventional ion implanted material, which could be partially attributed to the deeper and tougher surface modified layer produced by PIII than by CII. Experimental results also indicate that the depth of the PIII-modified layer, revealed by direct cross-sectional TEM observations and EDX analyses, is much larger than that estimated by the TRIM simulation.

References

1. H. DONG and T. BELL, *Surf. Coat. Technol.* **111** (1999) 29.
2. A. TUROS, J. JAGIELSKI, A. PIATKOWSKA, D. BIELINSKI, L. SLUSARSKI and N. K. MADI, *Vacuum* **70** (2003) 201.
3. R. HUTCHINGS, G. A. COLLINS and J. TENDYS, "Modification of Metals by Ion Beams," *Proc. 7th Int. Conf. on the Surf.* (Washington DC, 1991) p. 15.
4. A. TOTH, I. BERTOTI, E. SZILAGYI, H. DONG, T. BELL, A. JUHASZ and P. M. NAGY, *Surf. Interf. Anal.* **30** (2000) 434.
5. W. SHI, X. Y. LI and H. DONG, *Wear* **250** (2001) 544.
6. D. B. WILLIAMS and C. B. CARTER, "Transmission Electron Microscopy—A Textbook for Materials Science" (Plenum Press, New York, 1996) p. 353.
7. ANDRE ANDERS, "Handbook of Plasma Immersion Ion Implantation and Deposition" (John Wiley & Sons, New York, 2000).
8. W. SHI, PhD thesis, The University of Birmingham, 2001.

Received 10 October
and accepted 24 November 2003