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Wear-resistant steel surfaces obtained by high dose implantation of carbon

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Abstract

Carbon ions were implanted into hardened and unhardened Sverker 21 and Thyrapid 3243 steels with doses ranging between 0.5×10^{18} and 2.0×10^{18} C^+ cm^{-2} and with ion energies of 75 and 150 keV. Friction and wear were measured with pin-on-disk tribometers, both unidirectional and reciprocating. The coefficient of friction was moderately reduced, from about 0.8 to 0.2–0.5, by the surface modification induced. In several cases a dramatic decrease in wear was observed. The wear behaviour was very dependent on the tribological test conditions (unidirectional or reciprocating test, relative humidity and test atmosphere (air, O_2 or N_2)).

Stoichiometry and structural properties were investigated with Auger analysis, transmission electron microscopy and selected-area electron diffraction. The ion-carbonized surfaces were amorphous, and peak carbon concentrations of up to around 90 at.% were measured. The main part of the implanted carbon was present as graphite or amorphous carbon.

1. Introduction

Ion implantation has been developed during the last two decades as a method of modifying the near-surface region of metals with respect to chemical and mechanical surface properties. In particular, implantation of nitrogen into different types of tool steel has shown marked improvements in tool lifetime even under harsh production conditions [1]. However, it is also well known that, in other cases (material or working conditions), nitrogen implantation has not been able to improve the tribological behaviour. Ion implantation of for instance boron [2], titanium and/or carbon [3, 4] are other possibilities. By means of carbon implantation it is possible to reduce the coefficient of friction and wear rate substantially for an unlubricated sliding wear couple. It is possible in some cases to change the wear mode from adhesive to abrasive. In the present work, high dose carbon implantation of Sverker 21 steel and Thyrapid 3243 steel is investigated and compared with nitrogen implantation of the same steels.

2. Experimental details

2.1. Sample preparation

Test samples of hardened and unhardened cold-worked steel and high speed steel were used for the experiments. The cold-worked steel was Sverker 21 (No. 1.2379) with a Brinell hardness of 210 HB (unhardened state), and the high-speed steel was Thyrapid 3243 (No. 1.3243) with a Brinell hardness of 240–300 HB (unhardened state). The chemical compositions of the two steels are shown in Table 1.

The steels were cut into disks with a diameter of 28 mm and a thickness of 5 mm. Some of the Sverker 21 disks were hardened in a vacuum oven at 1020 °C, cooled in forced convection with N_2, tempered for 2 h at 160 °C and tempered for 2 h at 480 °C. The resulting Rockwell C hardness was 58–59 HRC.

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TABLE 1

Chemical compositions of Sverker 21 steel and Thyrapid 3243 steel

	C	Si	Mn	Cr	Mo	V	W	Co	Fe
Sverker 21 steel									
Amount (wt.%)	1.55	0.3	0.3	12.0	0.8	0.8	—	—	Balance
Amount (at.%)	6.8	0.6	0.3	12.1	0.4	0.8	—	—	Balance
Thyrapid 3243 steel									
Amount (wt.%)	0.92	—	—	4.1	5.0	1.9	6.4	4.8	Balance
Amount (at.%)	4.4	—	—	4.5	3.0	2.1	2.0	4.7	Balance

Some of the Thyrapid 3243 disks were hardened in a vacuum oven from 1220 °C, cooled in forced convection with N_2, tempered for 2 h at 550 °C, tempered for 2 h at 550 °C and tempered for 2 h at 560 °C. The resulting Rockwell C hardness was 63–65 HRC.

It should be noted that the above-mentioned hardening procedure for Sverker 21 steel resulted in a retained austenite content of only 6%, while the more usual procedure with a second tempering at about 200 °C results in a retained austenite content of 16% but a hardness similar to the above-mentioned value. Earlier investigations [5, 6] have shown that the retained austenite content can be very important for the results that can be obtained when using nitrogen ion implantation for improved wear resistance.

Before implantation, the disks were polished with diamond paste to a roughness R_a of below 10 nm and ultrasonically cleaned with trichlorethane, acetone and ethanole.

2.2. *Ion implantation*

Both hardened and unhardened disks were implanted with carbon ions at energies of either 75 or 150 keV and with doses of 0.5×10^{18}, 1.0×10^{18} or 2.0×10^{18} C^+ cm^{-2} in a Danfysik 1090-200 high current implanter [1, 7]. The ion beam was focused to a spot with a diameter of about 1 cm and the beam spot was scanned across the disks. In all cases the beam current was 0.65 mA of C^+ ions. For the 75 keV implantations the resulting average power density on the disks was (from lowest to highest dose) 0.5, 0.9 and 0.6 W cm^{-2}. The 150 keV implantations resulted in twice the power density for the corresponding doses. During implantation, the disk surface temperature was controlled with a pyrometer and was kept below 200 °C; the pressure in the target chamber was always kept between 1.0×10^{-5} and 3.0×10^{-5} mbar.

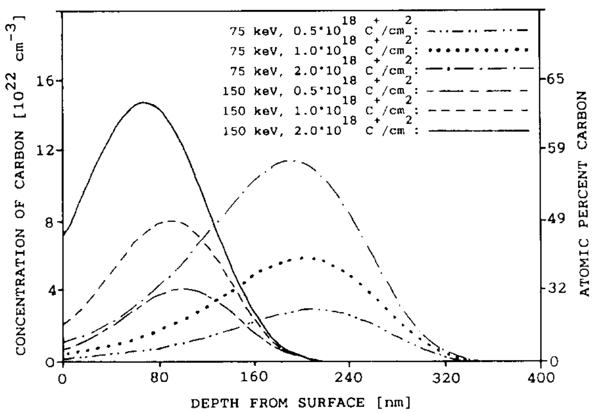

Fig. 1. Depth profiles of various carbon implantations in Sverker 21 steel calculated by the PROFILE CODE computer program. The profiles exclude the bulk carbon concentrations.

The calculated profiles in Fig. 1 (calculated with the PROFILE CODE [8]) should in the present case be looked at only as an indicator of the expected ion distribution because of the complicated nature of high dose implantations [9] (see also Section 3.4).

For comparison, unhardened disks of Sverker 21 and Thyrapid 3243 were implanted with nitrogen ions at energies between 50 and 200 keV with doses ranging between 1×10^{17} and 8×10^{17} N^+ cm^{-2}. These are typical implantation parameters for nitrogen implantation of tool steels.

2.3. *Friction and wear tests*

The samples were tested with a unidirectional pin-on-disk tribometer (Cygnus II). The machine is a modified version of the standard pin-on-disk machine from Swansea Tribology Centre, UK.

The pin end is a ball of SKF3 steel (100Cr6) with a diameter of 5 mm. During the tests it was sliding against the rotating disk with a normal load of 2.4 N. The sliding speed was 0.1 m s^{-1} and the diameter of the wear track was 17.4 mm on the carbon implanted disks and 20 mm on the nitrogen-implanted disks. The change in diameter is considered to cause only a negligible change in the wear situation. This has been confirmed for the unimplanted samples. The tests were performed under unlubricated conditions in an atmosphere of air with 40%±5% relative humidity (RH). Other samples were tested with different RH values and other atmospheres (O_2 and N_2) for examination of the chemistry of the wear process. The temperature of the test atmosphere was in all cases kept at 25±3 °C. The coefficient of friction was measured continuously during the tests, and the diameter of the wear scar on the ball was measured after 150, 400, 750 and 1000 m. The volumetric wear of the ball was normalized to the contact pressure. The test was finally stopped after 1000 m, and the profile area of the wear track on the disk was measured with a Dektak 3030 profilometer. The measurements were taken at four positions (separated by 90°) along the circular track. An average value was found and the empirical standard deviation was determined. The positive or negative sign of the area will indicate whether material has been transferred to (positive) or from (negative) the disk.

Some of the samples were also tested with a reciprocating pin-on-disk tribometer for comparison. A ball of the same type as in the test with the unidirectional tribometer was sliding against the disk in a linear reciprocating movement with an amplitude of 2 mm and a frequency of 7 Hz. In this case, the load was 2.1 N, and the test atmosphere was air with 40%±10% RH. The volumetric wear of the ball normalized to contact pressure was determined after certain sliding distances. The profile area of the wear track was measured at the same distances.

3. Experimental results and discussion

3.1. Friction and wear tests in air with 40% relative humidity

Figure 2 shows the normalized volumetric wear of the ball *vs.* the sliding distance for the various implanted hardened Sverker 21 disks tested by the unidirectional tribometer in an atmosphere of air with an RH of 40%. Improvements in the ball wear range from a modest effect for the lower dose implantations (0.5×10^{18} and 1.0×10^{18} C^+ cm^{-2}) at 150 keV to very distinct improvements for the higher dose implantations

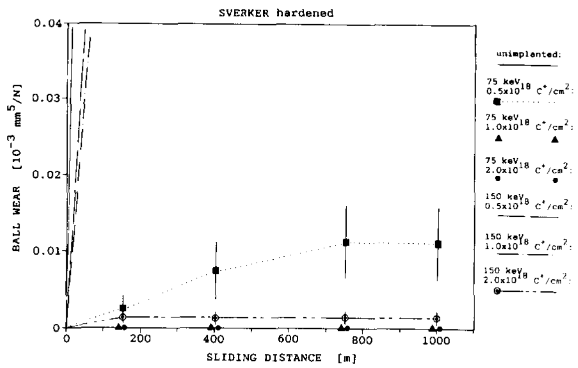

Fig. 2. Volumetric wear of ball normalized to contact pressure *vs.* sliding distance for carbon-implanted disks of hardened Sverker 21 steel.

(1.0×10^{18} and 2.0×10^{18} C^+ cm^{-2}) at 75 keV. The high energy (150 keV), high dose (2×10^{18} C^+ cm^{-2}) implantation gives a similar low wear rate after a running-in period. The running-in period may be defined as the time that it takes to wear off the outer surface layer of the disk with a relatively low concentration of carbon. The wear improvement seems only to be obtained in regions where the carbon concentration exceeds a certain level (see further discussion below). From Fig. 1 it can thus be expected that low energy, high dose implantations would result in immediate improvements whereas high energy implantations would only yield improvements after a certain running-in period. Figure 1 also shows that for a given dose the peak concentration is highest for the lowest implantation energy. For the above-mentioned high energy, low dose implantations, the critical ion concentration does not seem to be reached.

Again this is in accordance with results of tests of the hardened Thyrapid 3243 disks (results not shown here). The disks subjected to low energy, high dose implantation yield immediate and substantial improvements. The disks undergoing low energy, low dose and high energy, high dose implantation yield similar, extremely low wear rates after a running-in period, and finally the high energy, low dose implantations with the lowest peak concentration of carbon yield only very modest improvements in wear rate.

It is also possible to understand the results from tests of the unhardened disks (results not shown here) using the same arguments. The running-in period is typically much shorter for the unhardened disks. It is expected that the surface layer is worn off more rapidly for the softer steels. Furthermore, after some time a break-

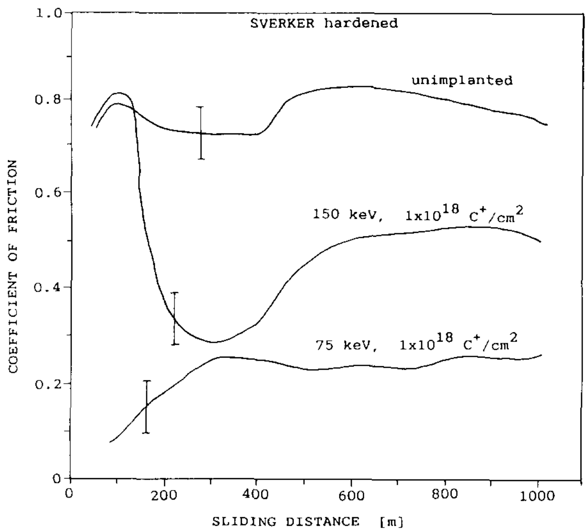

Fig. 3. Coefficients of friction *vs.* sliding distance for unimplanted and carbon-implanted disks of hardened Sverker 21 steel.

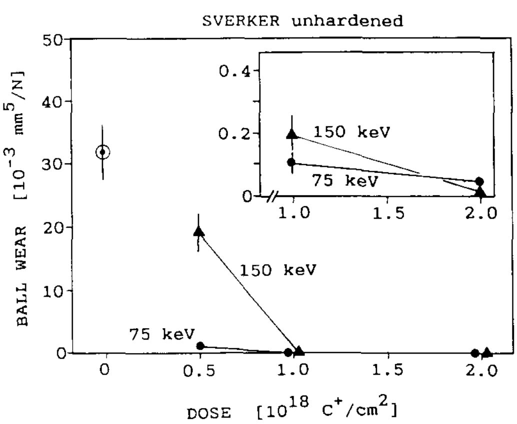

Fig. 4. Volumetric wear of ball normalized to contact pressure after 1000 m sliding distance for disks of unhardened Sverker 21 steel, carbon implanted with different doses at 75 and 150 keV. The inset shows an enlargement of the ball wear scale for doses of 1.0×10^{18} and 2.0×10^{18} C^+ cm^{-2}.

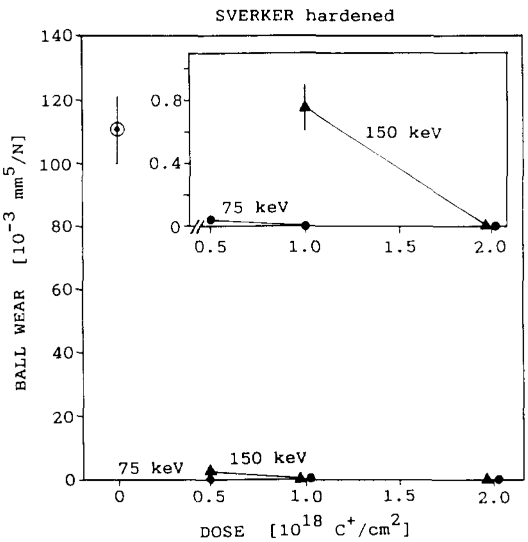

Fig. 5. Volumetric wear of ball normalized to contact pressure after 1000 m sliding distance for disks of hardened Sverker 21 steel carbon implanted with different doses at 75 and 150 keV. The inset shows an enlargement of the ball wear scale for doses of 0.5×10^{18}, 1.0×10^{18} and 2.0×10^{18} C^+ cm^{-2}.

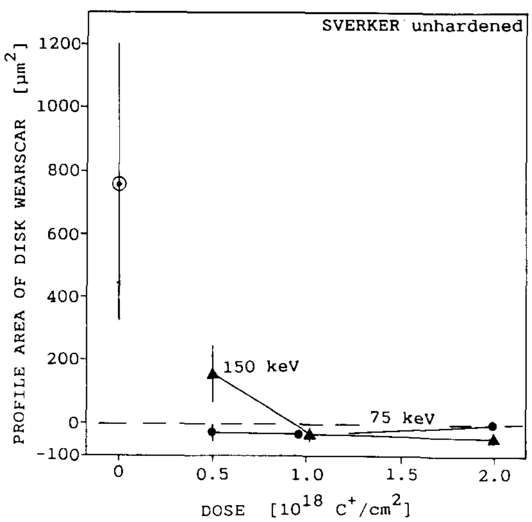

Fig. 6. Mean values and empirical standard deviations of profile areas of disk wear scars after 1000 m sliding distance for disks of unhardened Sverker 21 steel carbon implanted with different doses at 75 and 150 keV.

through effect occurs. This break-through occurs first (typically around 400 nm) for the softer unhardened Sverker 21 steel.

Typical coefficients of friction for various implanted hardened Sverker 21 disks are shown in Fig. 3. The friction coefficient is reduced from about 0.8 for the unimplanted disk to the rather low value of about 0.2 for the disk implanted with a dose of 1×10^{18} C^+ cm^{-2} at 75 keV. The disk implanted with the same dose at 150 keV goes through a running-in period with no reduction in coefficient of friction and reaches an intermediate value of about 0.5 at the end of the test. Again, a likely explanation of the occurrence of the running-in period prior to obtaining a low coefficient of friction could be that the reduction is initiated subsequent to the wearing-off of the outermost layer of the disk containing a relatively low carbon content.

Figures 4 and 5 show the normalized wear of the ball, and Figs. 6 and 7 show the profile area of the wear track on the various implanted unhardened and hardened Sverker 21 disks after a

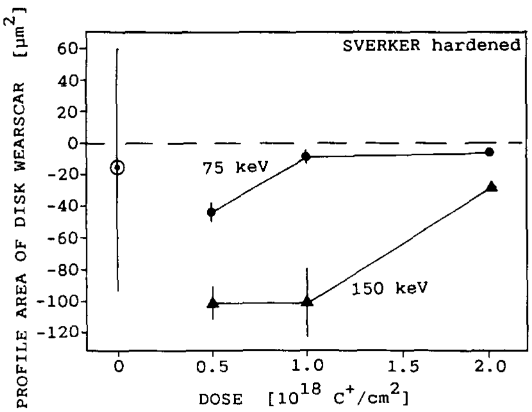

Fig. 7. Mean values and empirical standard deviations of profile areas of disk wear scars after 1000 m sliding distance for disks of hardened Sverker 21 steel carbon implanted with different doses at 75 and 150 keV.

1000 m test with the unidirectional tribometer in air with an RH of 40%.

The wear of the ball sliding against the unhardened Sverker 21 disk (Fig. 4) is substantially reduced by the higher dose implantations.

The wear scar on the unimplanted unhardened Sverker 21 disk (Fig. 6) is very inhomogeneous, showing a large standard deviation of the profile area. In the case of the unimplanted disk the situation is dominated by material transfer (adhesion) to the disk with a positive value of the profile area. Except for the 0.5×10^{18} C^+ cm^{-2}, 150 keV implantation (lowest carbon concentration), the disk wear is changed by implantation to a situation where material is removed from the disk (abrasive wear), and the magnitude of the profile area is considerably reduced by all the tested implantations.

For the hardened Sverker 21 steel, the high dose implantations result in a considerable reduction in the ball wear (Fig. 5). After 1000 m sliding distance, the wear is $(0.04 \pm 0.01) \times 10^{-3}$ mm^5 N^{-1} for the ball sliding against the hardened disk implanted with a dose of 2×10^{18} C^+ cm^{-2} at 150 keV. For implantation with the same dose at 75 keV, no ball wear could be seen above the observation limit of 10^{-9} mm^5 N^{-1}.

The wear scar on the unimplanted but hardened Sverker 21 disk (Fig. 7) is relatively small but very inhomogeneous, showing a large standard deviation of the profile area. In all the implanted situations, material is worn off the disk in a very homogeneous way (low standard deviation). The 75 keV, high dose implantations give the best results. On average the amount of worn-off material is not significantly less than for the unimplanted disk, but the implantation yields a very homogeneous wear track. The high energy, low dose implantations tend to give an increase (also compared with the unimplanted disk) in amount of worn-off material from the disk. The high energy, high dose implantation gives a result similar to what is obtained with low energy, low dose implantation.

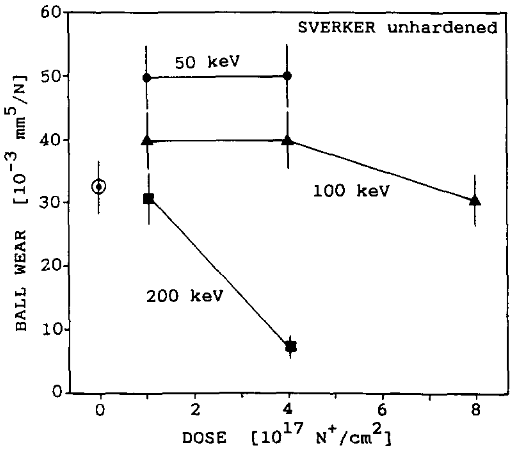

Fig. 8. Volumetric wear of ball normalized to contact pressure after 1000 m sliding distance for disks of unhardened Sverker 21 steel nitrogen implanted with different doses at 50, 100 and 200 keV.

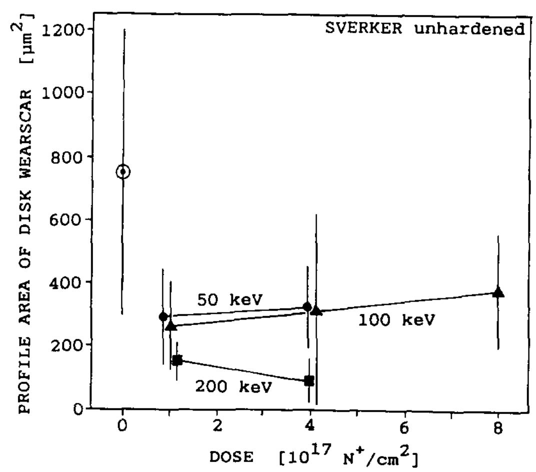

Fig. 9. Mean values and empirical standard deviations of profile areas of disk wear scars after 1000 m sliding distance for disks of unhardened Sverker 21 steel nitrogen implanted with different doses at 50, 100 and 200 keV.

The ball wear and profile area of disk wear scars for corresponding tests of various nitrogen-implanted unhardened Sverker 21 disks are shown in Figs. 8 and 9. The implantation doses and energies are typical for nitrogen implantation of production tools. Nitrogen implantation with doses of around 10^{18} N^+ cm^{-2} would result in a very high nitrogen concentration at the surface. The highly concentrated nitrogen would tend to form bubbles and subsequently blisters at the surface, having a deleterious effect on the tribological behaviour of the steels. In general, the wear is reduced to a considerably smaller extent by the nitrogen implantations than by the high dose carbon implantations when tested under the present conditions.

It is noticeable that, for carbon implantation with a fixed dose, the improvement of the wear situation is most significant for the lowest energy, as is evident from Figs. 2–7, while for nitrogen implantation the highest implantation energy tends to yield the strongest improvement, as may be seen from Figs. 8 and 9.

It should be noted that the above-mentioned nitrogen implantations have not been followed by a heat treatment or annealing. Several experiments have recently shown that annealing after nitrogen implantation can yield a substantial further improvement in surface hardness (about 40%) [10, 11] and tribological behaviour in general [12]. In ref. 12, nitrogen implantation of a punch reduced the wear rate compared with the unimplanted case by a factor of 1.2. Nitrogen implantation followed by a heat treatment reduced the wear rate by a factor of 5 compared with the unimplanted case.

Some of the carbon-implanted disks were also tested with the reciprocating tribometer in air with an RH of 40% ± 10%. Figure 10 shows the ball wear *vs.* sliding distance for the unhardened Sverker 21 implanted with a dose of 2×10^{18} C^+ cm^{-2} at 75 keV as measured with both tribometers. The ball wear rate measured with the unidirectional tribometer seems rather constant during the 1000 m sliding distance. Quite a different development of the ball wear rate is seen when measured with the reciprocating tribometer. A very low wear rate is observed up to a sliding distance of around 700–800 m, followed by a steep increase showing a break-through behaviour. When comparing the same wear data as a function of number of passages of the ball over a given point of the wear track, distinct differences are again evident. For the unidirectional test a severe wear rate is seen right from the beginning. For the reciprocating test a low wear rate is seen up to around $(3-4)\times10^5$ passages. From there the wear rate increases dramatically and at around 5×10^5 passages it has reached a wear rate value similar to that measured for the unidirectional test.

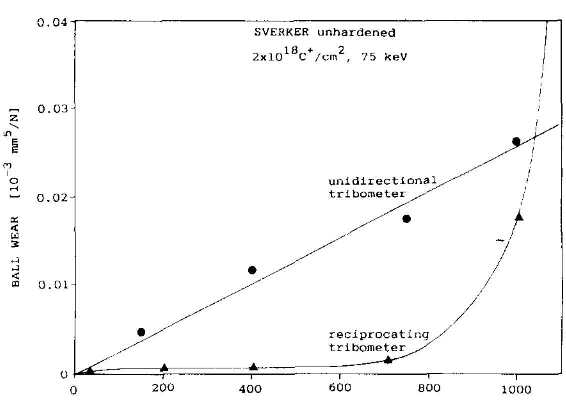

Fig. 10. Volumetric wear of ball normalized to contact pressure *vs.* sliding distance for tests with the unidirectional and with the reciprocating tribometer of disks of unhardened Sverker 21 steel carbon implanted with 2×10^{18} C^+ cm^{-2} at 75 keV.

The unidirectional tribometer distributes the disk wear over a circular track 55 mm long every point of which is passed by the ball 1.8 times per second. The reciprocating tribometer distributes the disk wear over a track only 2 mm in length every point of which is passed 14 times per second, leaving much less time for surface oxidation of the wear track between each passage. On the contrary, the concentration of dissipated heat and thus oxide growth rate must be much larger for the reciprocating test. The resulting wear will be very dependent on the balance between breakdown of the surface oxide layer with each passing and the regrowth of the oxide layer in between. The differences in track length and time between passages and hence concentration of dissipated heat may thus explain the difference in wear behaviour.

3.2. *Friction and wear tests in different atmospheres*

Unhardened disks of Sverker 21 and Thyrapid 3243, implanted with a dose of 2×10^{18} C^+ cm^{-2} at 150 keV were tested with the unidirectional tribometer in various test atmospheres. The resulting ball wear and profile area of the disk wear are shown in Table 2. The ball wear was low for test atmospheres of O_2 (Thyrapid 3243 disk) and air with 21% O_2 (Sverker 21 disk) both with an RH of 40%. It was also low for air with an RH of 95% (Sverker 21 disk). The ball wear was relatively high when the test atmosphere was dry O_2 (Thyrapid 3243 disk) or dry air (Sverker 21 disk). For dry N_2 the wear of the ball sliding against a

TABLE 2

Wear results for unhardened disks of Sverker 21 steel and Thyrapid 3243 implanted with a dose of 2×10^{18} C^+ cm^{-2} at 150 keV and tested in different atmospheres

Steel type of unhardened disk	Test atmosphere	Relative humidity (%)	Normalized ball wear ($\times 10^{-3}$ mm^5 N^{-1})	Profile area of disk wear scar (μm^2)
Thyrapid 3243	O_2	≈0	0.8 ± 0.2	188 ± 32
Thyrapid 3243	O_2	40	0.008 ± 0.004	-43 ± 7
Sverker 21	Air	≈0	0.50 ± 0.10	199 ± 87
Thyrapid 3243	Air	40	0.08 ± 0.02	-57 ± 3
Sverker 21	Air	40	0.018 ± 0.007	-42 ± 4
Sverker 21	Air	95	0.026 ± 0.010	-50 ± 15
Thyrapid 3243	N_2	≈0	0.60 ± 0.10	-15 ± 19
Sverker 21	N_2	≡0	0.14 ± 0.04	-13 ± 10
Thyrapid 3243	N_2	40	1.2 ± 0.2	-29 ± 9

Sverker 21 disk was still relatively low (but larger than for humid O_2 and air). For a ball sliding against a Thyrapid 3243 disk in dry or humid N_2 the wear was relatively high. It should be noted, however, that the highest ball wear measured in the present examples was $(1.2 \pm 0.2) \times 10^{-3}$ mm^5 N^{-1}. This is still low compared with the measured ball wear for unimplanted disks. The wear of the ball sliding against an unimplanted unhardened Sverker 21 disk in air with 40% RH was $(32 \pm 4) \times 10^{-3}$ mm^5 N^{-1} (Fig. 4). For an unimplanted unhardened Thyrapid 3243 disk the corresponding ball wear is $(44 \pm 5) \times 10^{-3}$ mm^5 N^{-1}.

In order to obtain very low wear of the ball sliding against the unhardened carbon implanted disks it thus seems important that both O_2 and water moisture are present in the atmosphere.

The wear of the disk is also dependent on the test atmosphere. Tests in an atmosphere of dry O_2 (Thyrapid 3243 disk) or dry air (Sverker 21 disk) resulted in large positive profile areas (adhesion) of 188 ± 32 μm^2 and 199 ± 87 μm^2 respectively. It should be mentioned that the corresponding results for unimplanted, unhardened Thyrapid 3243 and Sverker 21 disks tested in air with 40% RH were 580 ± 260 μm^2 and 750 ± 430 μm^2 respectively. So some improvement is still obtained under these conditions.

In an optical microscope the material transferred to the disks appears as black coloured plateaux, the height of which was measured with the profilometer to be about 1 μm. Tests in the other atmospheres (including dry N_2) resulted in profile areas ranging from -13 ± 10 μm^2 to -57 ± 3 μm^2. The negative values with low standard deviations demonstrate that material has been worn off from the disks in a rather uniform way along the wear tracks. In these atmospheres the wear mode is thus of quite a different character (abrasive wear) from the wear modes in atmospheres containing dry O_2 or dry air. The results can be divided into three types: (1) atmospheres of dry O_2 or dry air, high ball wear and very large material transfer to the disk; (2) atmospheres of dry or humid N_2, medium to high ball wear and low abrasive wear of the disk; (3) atmospheres of humid O_2 or humid air, low ball wear and medium abrasive wear of the disk.

3.3. Transmission electron microscopy and selected-area electron diffraction analysis

300 kV transmission electron microscopy (TEM) and selected area electron diffraction (SAED) were used to characterize the hardened Sverker 21 steel implanted with carbon with a dose of 2×10^{18} C^+ cm^{-2} at 150 keV. A free-standing surface layer was made by back-thinning the implanted disk in a jet electropolishing process. In Fig. 11 a bright field TEM micrograph of the layer 100–200 nm thick used for SAED analysis is shown. The surface layer seems rather homogeneous with a dense pattern of grained structures with diameters between 10 and 100 nm. In Fig. 12(a) an SAED pattern for an area with a diameter of about 2 μm is shown. This pattern consists of very diffuse concentric rings and clearly demonstrates that the layer is at least partly amorphized. Similar investigations of unimplanted samples show that this has been induced by the implantation. A corresponding SAED pattern for an area with a diameter of

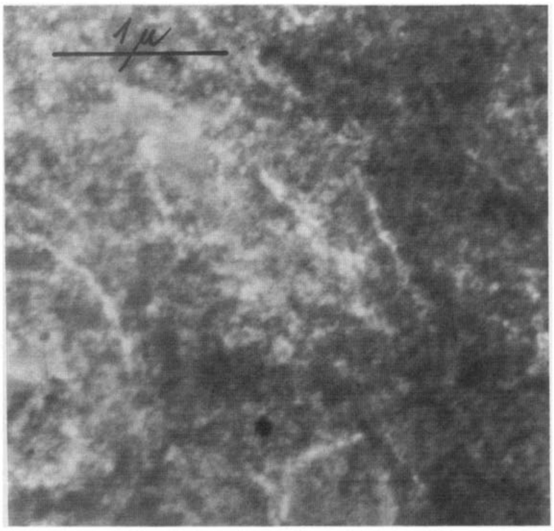

Fig. 11. Bright field transmission electron micrograph of the surface layer of hardened Sverker 21 steel carbon implanted with 2×10^{18} C^+ cm^{-2} at 150 keV.

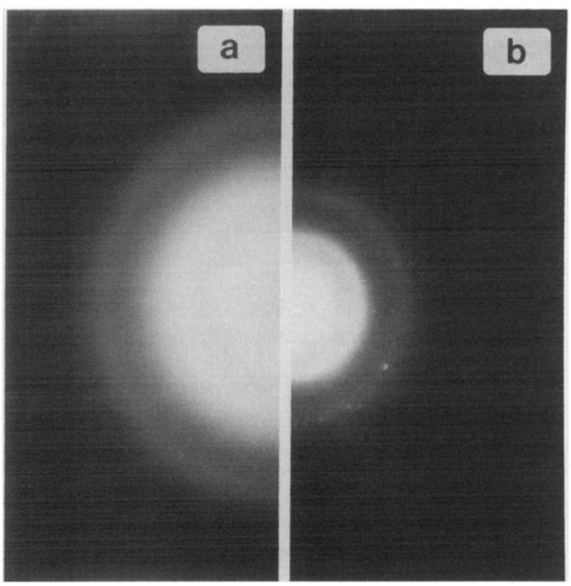

Fig. 12. Electron diffraction pattern for the surface layer of hardened Sverker 21 steel carbon implanted with 2×10^{18} C^+ cm^{-2} at 150 keV: (a) diffraction area with a diameter of about 2 μm; (b) represents a diffraction area with a diameter of about 0.2 μm. The small spots in one of the rings in (b) should be noted.

about 0.2 μm of the implanted sample is shown in Fig. 12(b). The diffuse rings are still visible, but small spots in one of the rings indicate that microcrystals are present in the area.

Very recently, the microstructures of some carbon-implanted steels with different chromium contents were investigated [13]. By SAED analysis it was found that the stainless steels AISI 304 (19 at.% Cr; f.c.c. structure) and AISI 440C (17 at.% Cr; b.c.t. structure, equivalent to a martensitic structure), and two special alloys, Fe–18at.%Cr and Fe–12at.%Cr (b.c.c. structure), would all be amorphized by carbon implantation when the total concentration of implanted and bulk carbon exceeded a minimum concentration. This minimum concentration C_m was found to be about 23 at.% C for Fe–12at.%Cr and about 20 at.% C for Fe–18at.%Cr. Crystalline ε-carbides were formed instead by implantation with lower carbon concentrations. Another special alloy (Fe–6at.%Cr) could not be amorphized, but only ε-carbide particles with a diameter of about 50 nm were formed, even for implanted carbon concentrations up to 50 at.%. It was concluded that steels with at least about 12 at.% Cr or other carbide-forming elements (e.g. molybdenum, titanium, vanadium and tungsten) will be amorphized by carbon implantation with a sufficient concentration.

The Sverker 21 steel contains 6.8 at.% C, 12.1 at.% Cr and minor amounts of other carbide formers and should therefore be amorphous in the layer where the total carbon concentration exceeds $C_m \approx 23$ at.% C, *i.e.* where the concentration of implanted carbon exceeds about 16 at.%. According to the calculated profile (Fig. 1) and the above arguments, it could thus be expected that for the 2×10^{18} C^+ cm^{-2}, 150 keV implantation the material would be amorphized in a layer depth between about 20 and about 300 nm, while the layer closer than about 20 nm to the surface should contain carbides and possibly some surface oxides. This would agree with the mixed amorphous–microcrystalline appearance of the SAED pattern in Fig. 12(b). The depths found by using the PROFILE CODE calculations should only be taken as indications and not as exact numbers (see also Section 3.4).

All the implanted Sverker 21 disks used in the friction and wear tests have sufficiently high implanted carbon concentrations to ensure amorphization of a region below the surface. The Thyrapid 3243 disks contain only 4.5 at.% Cr but large amounts of other carbide formers (see Table 1); so it is likely that these disks have also been amorphized by the carbon implantations. TEM analyses are proceeding with the aim of obtaining a better understanding of the correlation between the microstructure and the tribological behaviour of the implanted disks. In total there seems to be a strong correlation between high carbon concentration, and thus amorphization, and low wear rates and low coefficients of friction.

3.4. Auger analyses

In order to check the profiles of implanted ions as calculated with the PROFILE CODE and to investigate the stoichiometry of the implanted material, some of the unhardened and carbon implanted Sverker 21 disks (75 keV C^+; 2×10^{18} C^+ cm^{-2}) are being investigated by means of Auger depth profile analyses. The investigations are not finished, but the preliminary results indicate a somewhat broader profile than shown in Fig. 1 for this implantation. The difference is probably partly caused by an underestimation in the calculations of the decrease in stopping power of the target as the implanted carbon dose increases. This effect will be most significant for the highest doses. The ongoing measurements further indicate carbon peak concentrations above 80 at.%. This has been confirmed by Rutherford backscattering spectroscopy, but it seems to be an extremely high concentration even for the high implantation dose and will be re-investigated. Further Auger measurements showed that, as could be expected, the main part of the carbon is present as graphite or amorphous carbon and not as carbides.

4. Conclusions

The present results show that it is possible to obtain substantial tribological improvements on steels by high dose carbon implantation. The degree of improvement has been shown to depend on the test atmosphere and other test conditions. The best results seem to be obtained in atmospheres containing O_2 and water vapour. The improvements obtained by high dose carbon implantation are substantially better than the results obtained by standard nitrogen implantation without subsequent heat treatment and even better than typical results obtained by nitrogen implantation followed by heat treatment.

A certain lower threshold level concentration of carbon seems to have to be exceeded to obtain the improvements, and the available data indicate that this level could be the carbon concentration level at which the steels are amorphized.

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