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Ion implantation as an efficient surface treatment

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Ion beam processing has for several years been well established in the semiconductor industry. In recent years ion implantation of tool steels, ceramics and even plastics has gained increasing industrial awareness. The development of ion implantation to a commercially viable surface treatment of tools and spare parts working in production type environments is very dependent on technical merits, economic considerations, competing processes and highly individual barriers to acceptance for each particular application. Some examples of this will be discussed. The development of the process is very closely linked with the development of high current accelerators and their ability to efficiently manipulate the samples being treated, or to make sample manipulation superfluous by using special beam systems like the PSII. Furthermore, the ability to produce high beam currents (mA) of a wide variety of ions is crucial. Previously, it was broadly accepted that ion implantation of tools on a commercial basis generally had to be limited to nitrogen implantation. The development of implanters which can produce high beam currents of ions like B^+, C^+, Ti^+, Cr^+ and others is rapidly changing this situation, and today an increasing number of commercial implantations are performed with these ions although nitrogen is still successfully used in the majority of commercial implantations. All in all, the recent development of equipment makes it possible to a higher extent than before to tailor the implantation to a specific situation. The emerging new possibilities in this direction will be discussed, and a broad selection of practical examples of ion implantation at standard low temperatures of tools and spare parts will be given. Furthermore, very interesting results have been obtained recently by implanting nitrogen at elevated temperatures, which yields a relatively deep penetration of the implanted ions. Besides various examples of direct ion implantation, the very cost-effective variation based on ion bombardment of the sample surfaces in a controlled atmosphere of oil vapour will be discussed and compared to recent investigations of high dose carbon implantations. Direct nitrogen implantation and implantation combined with nitriding of aluminium have both shown interesting tribological potential. Other and relatively new practical examples of ion implantation used for changing the tribological and other surface characteristics of ceramics and plastics will also be discussed.

1. Introduction

Ion implantation has rather a long history in the semiconductor industry, where it has been used since around 1960 to dope silicon wafers for use in the electronics industry [1]. Some of the great advantages that have been recognized in connection with this production are the high controllability, reliability and reproducibility of the process, and this has been the main reason for the continuing success of ion implantation in this area. In the early 1970s the industrial exploitation of the possibility of changing the tribological properties of production tools by ion implantation was pioneered at the Atomic Energy Research Establishment (AERE), Harwell, UK [2]. Since then a number of papers have been published, describing the tribological benefits in materials performance which can be obtained by ion implantation. Although a large number of technically successful improvements have been obtained by ion implantation, real commercial use of ion implantation for obtaining tribological improvements of tools and spare parts has emerged only in the last few years. There are many reasons for this, some of which will be discussed in this paper. An important parameter has been the development of equipment which could make the process commercially viable. The development of different types of accelerators will be discussed. The development of knowledge of the process, practical examples of obtained tribological improvements on production tools, and recently emerged ion implantation technologies aiming at improving tribological properties of materials will be discussed. Combinations of ion implantation and other surface treatments and ion implantation of ceramics and polymers are among the new developments.

2. Equipment

The development of ion implantation towards a viable commercial process for surface engineering of tool surfaces is very closely linked with the technical development of the process equipment, i.e. high current ion accelerators. For several years, investigations were performed on low current research accelerators or high current implanters based on techniques developed for doping silicon wafers. Clearly, the demands on implanters for the electronics and nonelectronics industry are very different. The demand for a "clean" beam is much higher for semiconductor implantations than for implantations for tribological use. Generally, other ion types are used, and the demands on the specimen manipulators are very different indeed. It is much easier to make a manipulator which can handle more or less uniformly shaped wafers than to make a manipulator/holder system which can handle tools and spare parts of very different shapes, sizes and weight.

The implanters for tribological improvement of materials surfaces can be divided into two main groups. One group consists of a relatively simple type of implanters which is not equipped with an analyzing magnet. These accelerators are only able to implant gaseous ions like for example nitrogen. Examples of some of these accelerators are described in refs. [3–6]. The advantages of these accelerators are that they are relatively simple, and of the accelerators which are used today, they are clearly the most suitable equipment for installation on the production floor. They are cheaper than the more advanced accelerators and the main part of industrial implantations performed today could in principle be performed with nitrogen ions with this type of accelerator. It should be mentioned that some of the above-mentioned accelerators, for example in ref. [5], can be equipped with an analyzing magnet. In general the possibilities for manipulating the ion beam is limited on the non-mass-analyzed accelerators. The beam spot is often rectangular (a few cm broad and 30–50 cm long [6]), and in some cases it is possible to scan the beam in one direction.

The more advanced accelerators like the accelerators produced by Danfysik A/S [7] and Whickham Ion Beam Systems [8] typically have an analyzing magnet and a layout like the one in fig. 1 showing the Danfysik 1090-200. A prototype of this equipment was installed at the Danish Technological Institute in 1987 and has since then been used for both R&D work and for service implantations for industry [9–11]. This accelerator has advanced facilities for focussing and defocussing the beam and for scanning the beam over a squared area of 400 mm × 400 mm. Recently, control of the beam scanning of this accelerator by means of a computer programme has been developed. This makes it possible to a very high degree to ensure that the ion beam is directed only towards surfaces chosen for implantation, and in this way a substantial increase in efficiency is obtained.

Often, and with good reason, it is mentioned that ion implantation has the drawback of being a line-of-sight process. For conventional ion implantation it is necessary to have a versatile specimen holder/manipulator. The Danfysik 1090-200 accelerator is equipped with a water-cooled target holder/manipulator which can rotate, tilt and move the specimens up and down during implantation. It is also possible to control these movements with a computer, and in many practical cases combining the computer control of the beam scanning and the target manipulator can increase the efficiency of the accelerator several times. The resulting efficient use of the ion beam

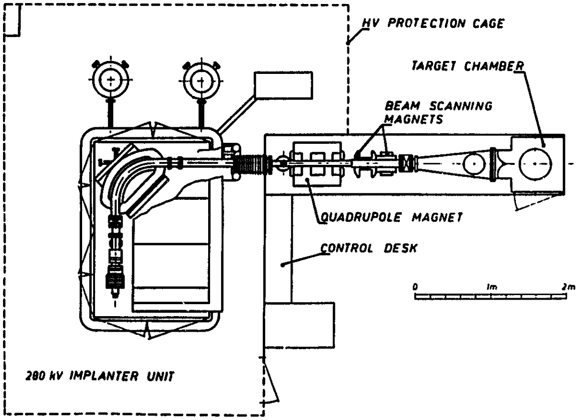

Fig. 1. Layout of the Danfysik 1090-200 high current implanter.

helps to reduce the price of an implantation. Since the kinetic energy of the ions is dissipated as heat in the target material, it is important both to have an efficient cooling system which does not limit the possibilities of manipulating the specimens and also to be able to scan the beam efficiently over a large area in order to reduce heating of the implanted samples without losing implantation time. A 5 mA ion beam of 200 keV ions will dissipate as much as 1 kW into the implanted samples, and if this is not spread over a large area or efficiently taken away by cooling, it will cause substantial heating of the samples.

The Danfysik and Whickham accelerators are able to produce ion beams with typical currents around 1–5 mA or more of a broad variety of both gaseous and metallic ions. Ions which are typically used for commercial implantations of tools are: N^+, B^+, C^+, Ti^+, Cr^+. The ions are produced either in a Chordis ion source (Danfysik) [7] with an annular outlet yielding a circular beam spot or in a Freeman ion source (Whickham) [8] with a slit shaped outlet yielding a rectangular beam spot. The beam spots can of course be shaped otherwise by focussing magnets.

Another type of accelerator which has been specialized for non-mass-analyzed high current metal ion beams has recently been developed. This is the so-called MEVVA accelerator [12,13]. This accelerator is reported to be able to produce ion beam currents of doubly charged metallic ions of around 20 mA in a circular beam spot on the target with a diameter of 250 mm.

In order to be able to carry out implantation of tools and spare parts of complicated shapes, it is necessary to equip both the non-mass-analyzed and the mass-analyzed accelerators with an advanced and complicated specimen holder/manipulator. Recently a different and very interesting system for implantation of nitrogen has been developed, which may prove able to solve this problem. The new type of implantion is the so-called plasma source ion implantation (PSII) [14–18] or plasma immersion ion implantation (PIII) [19]. The two processes are very alike, and no distinction will be made here. A layout of the PSII equipment can be seen in fig. 2.

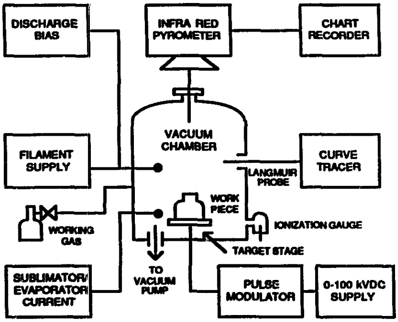

Fig. 2. Block diagram showing vacuum chamber power supplies and diagnostics of the plasma source ion implantation (PSII) device.

A plasma is created around the workpiece to be treated, and ions are extracted from the plasma and accelerated towards the workpiece. This more or less corresponds to putting the workpiece in the ion source of a conventional accelerator. It has been proved that it is possible to obtain good results with the PSII process on production tools, and further development of the process seems very interesting from a commercial point of view.

3. Standard implantations of tools

The use of ion implantation to improve tool performance in real production type environments has increased considerably in recent years. The majority of this type of implantations are still performed with nitrogen ions. However, the tendency is towards more diversified implantations. The development of versatile high current implanters has provided a commercially realistic possibility of implanting ions other than nitrogen into production tools and has thereby facilitated tailoring of implantations to a specific steel and to a specific wear situation to a higher degree than before. As a rule it is still cheaper to implant nitrogen ions than for example B^+, C^+, Ti^+, Cr^+. However, in an increasing number of cases the technical advantages gained by using these ions can outweigh the higher costs.

Although today knowledge of ion implantation of tools with nitrogen ions and other ions is substantial, a new tool from a customer is still often a new and nonroutine situation, and optimal implantation parameters have to be found. The first implantations for a new customer are therefore often performed as trial implantations. Besides, it is often the case that the customer is not able to specify what type of wear his workpiece is subjected to. It is not an unusual situation that a customer suspects his "wear problem" to be some kind of abrasive wear when in fact it turns out that corrosion plays an important part. In order to be successful with ion implantation of tools it is therefore very important whenever possible to investigate a new type of tool carefully before deciding which type of implantation is the best. Optimization of the treatment can often be problematic, because performing reliable laboratory tests which sufficiently well simulate real-life conditions is very difficult. And because of production demands in the company reliable, quantitative results from field tests can be very difficult to obtain.

However, the examples below describe successful implantations in which it was possible to overcome the intrinsic optimization problems, and in several of these cases a routine production has been obtained.

In the first example the chances of a successful optimization were good since the work was performed as part of a BRITE project (number 1357) among partners dealing with development of ion implantation and a company producing high precision punches for working electronic contact material [20]. The punches were made of Vasco Wear steel, and optimal implantation parameters were sought with C, N, B, Ti implantations. A lifetime improvement by a factor of 4.3 was obtained with B^+ implantation. The second best result was obtained with N^+ ions (improvement by a factor of 3.2). From a commercial point of view the nitrogen implantation would be the most advantageous. It can be performed for only 2 to 20% of the tool price, dependent on ion type and necessary ion dose.

Another important factor to be considered is that also after regrinding a substantial lifetime improvement remains. Traditionally, punching tools have been implanted both on the sides and on the end. By regrinding, the shallow implanted layer (thickness ≤ 0.3 μm) is always taken away on the punch end but not on the punch sides. In some cases it is therefore advantageous only to treat the punch sides. It has even been repeatedly documented that in some cases better lifetime improvements of punches are obtained after the first regrinding. This indicates that only the punch sides should be implanted. This is not fully understood yet. Some other successful examples are mentioned below.

Forming/cutting punches and dies working tin can material are today implanted on a purely routine basis. The tool material is D2 type steel which has been gas nitrided before nitrogen implantation. In general it is found that a combination of gas nitriding and ion implantation performs very well. These implanted forming/cutting tools perform better after the first regrinding than before. The lifetime between regrinds has been extended by a factor of 4 compared to tools which have only been gas nitrided.

Blanking dies of either AISI L6 or AISI H11 steel are another example. The steels are not nitrided but only nitrogen ion implanted. These tools are also working tin can material. On an average, the tools normally last around three weeks. After nitrogen implantation, the lifetime is increased to more than six months.

V-shaped knives for cutting dried leaf material (with sand particles incorporated) can be improved substantially by ion implantation. The knives are made of spring steel hardened to HRC 59. The implanted knives have been tested against normal knives and TiN (PVD) coated knives. Both standard nitrogen implantation and high dose carbon implantation have been tested. It turned out that the knives performed differently on the different testing machines. The improvements are therefore only comparable for tests performed with the same machine.

On machine I a comparison was made between standard, carbon implanted (100 keV C^+, 2×10^{18} C^+/cm^2) knives and TiN coated knives. On machine II a comparison was made between standard, nitrogen implanted (95 keV N^+, 4×10^{17} N^+/cm^2) knives and TiN coated knives. The knives were only implanted on one side of the cutting edge. After resharpening from the other side it was possible to maintain very good performance of the implanted knives. The results are presented in table 1.

Table 1
Lifetimes of the implanted knives

Knives	Ratio lifetime/ normal lifetime
Machine I	
Carbon	
new knives	4.0
resharpened knives	4.0
TiN	
new knives	2.5
resharpened knives	0.5
Machine II	
Nitrogen	
new knives	3.5
resharpened knives	4.0
TiN	
new knives	1.0
resharpened knives	0.5

Plastics can give severe abrasive wear on both nozzles, dies and moulds. For a particular set of nozzles it was very important that the dimensions and sharp edges of the inlet nozzles were retained very closely for as long as possible. The nozzles were made of werkst. no. 1.2363 steel, hardened to HRC 57 and implanted with nitrogen. The nozzles were removed from production for close inspection after having produced twice the normal amount of material. The investigation could not reveal any wear of the critical surfaces. The nozzles were put back into production, and until now they have produced more than four times what is normally feasible without any sign of degradation on the produced plastic parts. The nozzles are small, and several hundreds of them can be mounted in the target chamber in one batch. With computer controlled beam manipulation it is possible to utilize the ion beam optimally when treating the tools and thereby keep the treatment price low.

Heating needles are often used in the centre of inlet nozzles in order to heat the plastics at the inlet and to ensure an easy and homogeneous flow of the plastics material. These needles are often coated with hard chromium to reduce wear. By implanting nitrogen ions into the chromium, the lifetime of the needles can be prolonged substantially. Even after twice the normal lifetime for chromium coated needles no wear was visible on the nitrogen implanted chromium. Nitrogen implantation of hard chromium is rather a well established commercial surface treatment. Good results from nitrogen implantation of hard chromium coated industrial tools like plastic/rubber moulds, taps, draw punches, thread guides for TiO_2-containing yearn, and spare parts such as piston rings are reported in refs. [21–23]. By implanting nitrogen into hard chromium coatings it is possible to form CrN and Cr_2N. The chromium nitrides are harder than chromium, and the implanted ions create compressive stresses in the surface layer. Because of this, the microcracks inherent in most hard chromium layers tend to close, and the general tribological performance of the coatings is improved. The closing of microcracks also seems to improve the corrosion resistance. This is discussed in more detail in refs. [21–25].

Other interesting examples of obtained results on industrial components can be found in refs. [26,27]. Ref. [27] describes a very interesting investigation of the dependence of the performance of ion implanted punches and slitter blades on whether the worked material is cold or hot rolled steel. It seems that only minor improvements are obtained when the worked material is cold worked steel, whereas 2 to 12 times increase in wear life is obtained by ion implantation of M2 or D2 tools working hot rolled steel.

4. High dose carbon implantation and carbonaceous surface layers

Normally nitrogen implantation improves wear resistance of certain steels by different hardening mechanisms and by changing the surface oxide layer and thus changing severe wear to a mild oxidative wear situation. However, nitrogen implantation very seldom changes the coefficient of friction substantially. It has been known for several years that implantation of titanium plus carbon ions into steels can give good tribological effects. It is expected that an amorphous Fe–Ti–C surface layer is formed in this way. This gives good wear resistance and reductions in coefficients of friction. The process has for example produced good results on ball bearings. It has also been demonstrated that by having a relatively bad vacuum in the target chamber it is not necessary to implant carbon. Carbon ions seem to be gettered by the titanium ions during implantation, e.g. from the oil vapour diffusion into the chamber from a diffusion pump.

In recent years, however, more work has been put into investigating the tribological possibilities with high dose carbon implantation. Several examples of this are discussed in refs. [10,11,28–31]. In several of these investigations the ion dose has been as high as $2–3 \times 10^{18}$ C^+/cm^2. And the ion energy has typically varied between 75 and 150 keV. An exception to this is the data reported in refs. [30,31] where double implantations with ion energies of only 50 and 20 keV have been performed. This will more or less lead to a buildup of a pure carbon surface layer. In ref. [11] it has been shown that also 75 keV, 2×10^{18} C^+/cm^2 implantation leads to very high carbon concentrations at the surface. Based on curves calculated by the computer code "Profile Code" [32] it is concluded that the carbon concentration peaks at around 90 at.%. In ref. [11] it is argued that the accuracy of the calculations in this case is accurate to within 20%. The high carbon concentrations have also been confirmed by RBS and depth profiling analysis [10,28]. In ref. [28] it is shown that the hardness of 100 keV C^+ implanted AISI 52100 changes with the carbon dose and that a maximum value is obtained around $1.0–1.5 \times 10^{18}$ C^+/cm^2. At higher and lower doses the hardness decreases. In all the papers mentioned here it is found by pin-on-disk wear tests that the wear is reduced by several orders of magnitude for the highest carbon concentrations, and no direct correlation between wear resistance and hardness has been found.

Typical wear reduction obtained by nitrogen implantation in steel and tested in similar pin-on-disk configurations is lower than a factor of 10, and if the nitrogen dose is increased above $\approx 8 \times 10^{17}$ N^+/cm^2, blistering will seriously degrade the tribological performance of a steel surface.

In refs. [10,11] it is also found that there seems to be a critical carbon concentration below which no tribological improvement is obtained. In fig. 3 it can be seen that as well as reducing the wear, carbon implantation reduces the coefficient of friction. There seems to be strong correlation between the measured coefficient of friction for a 5 mm diameter SKF3 ($\approx$ AISI 52100) steel ball sliding against carbon implanted disks of Sverker 21 ($\approx$ AISI D2) steel in a pin-on-disk testing setup. This is discussed in more detail in ref. [11], and it is argued that the carbon implanted surface to some extent works as a solid lubricant.

High dose carbon implantations are at present being tested on punches and nozzles. Examples of tests on knives are mentioned above. The results are marginally better than those obtained with nitrogen implantation but not enough to justify the use of carbon instead of nitrogen. Nozzles used in connection with moulds for plastic forming have been successfully implanted with high dose carbon. The nozzles are made of steel with a low percentage ($\leq 1\%$) of chromium. On these nozzles nitrogen implantation gave no improvement whereas high dose carbon implantation yields a substantial lifetime improvement.

On M2 steel it has been possible to obtain good improvements in an area where ion implantation is not normally considered a good choice of surface treatment. The tools made of M2 steel are working at elevated temperatures and under severe stress in a steel cutting operation where a reduction of coefficient of friction is expected to be important. Both nitrogen and titanium plus carbon failed to improve the tool performance, but high dose carbon implantation gave a substantial improvement in performance.

Although the high dose carbon implantations look very interesting and promising from a technical point of view, they have one serious drawback, namely the high dose which makes it rather an expensive treatment. The process can probably only become commercially viable in areas where lifetime improvements are better than a factor of 10. However, new developments are emerging which may help to overcome this problem. In refs. [33–36] it is shown that very good results can be obtained with a process consisting in a combination of ion bombardment and evaporation technique which builds up a carbonaceous surface layer on steel surfaces. A sketch of the principle can be seen in fig. 4. Silicone oil is heated and evaporates into the target chamber. At the same time the target is bombarded with either nitrogen, titanium or argon ions. Very low coefficients of friction ($\mu \leq 0.05$) are found in pin-on-disk tests where 5 mm diameter balls of AISI 52100-like steel is sliding against the coated disks. For uncoated disks similar tests gave $\mu \approx 0.9$. Besides, the coefficient of friction is found to be almost independent of relative humidity of the test atmosphere for the coated samples. It is important to note that these coatings have been obtained with ion doses ranging from 5×10^{16} ions/cm^2 to 2×10^{17} ions/cm^2. These doses are even below typical doses for nitrogen implantations, and the commercial potential for this process seems very good.

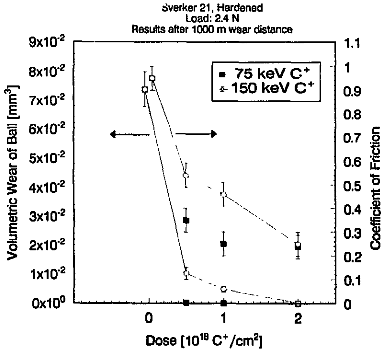

Fig. 3. The volumetric wear of the unimplanted AISI 52100 steel ball after 1000 m sliding distance against hardened and C$^+$ implanted Sverker 21 steel. The wear is shown as function of carbon dose and energy. The corresponding coefficients of friction are also shown.

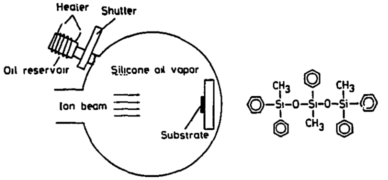

Fig. 4. Schematic illustration of setup for creating a carbonaceous surface layer from silicone oil vapour and ion bombardment. Chemical structure of silicone molecule is also shown.

5. Influence of temperature on ion implantation

Several authors have investigated the effects of elevated temperature on obtained results with nitrogen ion implantation. It is well known that elevated temperatures during implantation can have strong effects by changing the microstructure of steel specimens [36–39]. However, keeping a constant, elevated temperature of a workpiece during implantation is not simple. It is much easier to perform a subsequent heat treatment. In refs. [40,41] it has been shown that annealing after nitrogen implantation can yield a substantial further improvement in surface hardness by about 40%. In ref. [42] it has been shown how nitrogen implantation of a punch made of M2 steel reduced the wear rate by a factor of 1.2. Nitrogen implantation followed by heat treatment reduced the wear rate by a factor of 5. In ref. [43] two different stainless steels (AISI 304 and 310) were implanted with 2×10^{18} N$^+$/cm^2 at 400°C. Improvements in load bearing capacity by about a factor of 50 was measured. When implanting 100 keV N$^+$ into steel at temperatures below 200°C, a typical penetration depth is ≤ 0.3 μm. In ref. [43] nitrogen concentrations of about 20 at.% were measured down to depths above 0.8 μm. Besides obtaining improvements by implantation at elevated temperatures based on microstructural/chemical effects it also seems that in some cases it would be possible to use elevated temperature implantation to overcome the shallowness of ion implanted surfaces. Of course, high concentration of implanted ions down to substantial depths cannot be obtained without a higher ion dose than what is normally used, and this treatment could therefore be too expensive to become commercially viable. The PSII process does, however, seem to offer special possibilities in this direction also [18].

6. Combination of ion implantation and nitriding of aluminium

It was mentioned above that nitrogen implantation of gas nitrided tool surfaces often produces good tribological effects. It has recently been shown [44] that ion implantation before plasma nitriding can have a very interesting effect. It is found that implantation with for example 25 keV N_2^+ enhances the thickness of the nitriding layer for AISI 316 stainless steel by about 40%. And for aluminium a 1 mm thick 40% AlN layer was obtained by nitriding after ion implantation. The mechanisms are not well understood but the results look very interesting. There is a market for wear resistant aluminium surfaces in the plastic moulding industry as it is much easier to produce a mould in aluminium than in steel. Also, it is much easier efficiently to cool a mould made of aluminium than of steel. A steel mould is much heavier and therefore more difficult to handle than an aluminium mould. The only drawback is that the wear resistance of an aluminium mould is much smaller than the wear resistance of a steel mould. Aluminium moulds are therefore normally used only for small production or test series. With nitrogen implantation of aluminium moulds it has been shown that improvement of the mould lifetime by a factor of up to 4 is possible, and the process is slowly gaining acceptance in this area. The new process with a combination of low energy nitrogen implantation followed by a nitriding process might be able to extend the production sizes which can be covered by aluminium moulds.

7. Other combination processes

It has been shown in ref. [45] that interesting results can be obtained by combining laser surface hardening with ion implantation. It is well known that it is possible to harden steel surfaces by laser technique. The outermost layer of the surfaces is heated/melted by the laser beam, and the bulk material is used as a heat sink which cools the surface very quickly. The result is a harder and more wear resistant surface. However, it is also well known that this process creates rather strong tensile stresses in the surface. This has a negative effect on the wear resistance. By implantation of neon ions into the laser melted surface it is possible to compensate for the tensile stresses. The implanted neon ions will create compressive stresses, and the wear resistance of the laser hardened surface is found to increase by up to a factor of 5.

In recent years interest has also been given to combining ion implantation with PVD and CVD coatings. It has been experienced that it is possible to improve the wear resistance of TiN coatings on tools used for cutting operations by simple nitrogen or titanium implantations although the mechanisms are not well understood. In ref. [46] it has been shown that it is possible by implanting 80 keV carbon ions into PVD TiN films to create a TiCN film with improved fretting wear resistance compared to a normal TiN film.

8. Ion implantation of ceramics and polymers

Another and relatively new area in which ion implantation may play a future part is in changing the surface properties of ceramics and polymers. It has been shown [47] that it is possible to increase the surface hardness of Al_2O_3 by 30–40% by Cr^+ implantation. It is also possible to increase the flexural strength of Al_2O_3 by more than 20% by nitrogen implantation [48], and in ref. [49] it has been shown that it is possible by means of ion implantation to create lubrication of ceramics at elevated temperatures. In another investigation [50], for example, it was shown that implanting carbon ions into a ZrO_2 disk could reduce the wear of an Al_2O_3 ball sliding against the disk by several orders of magnitude.

It has been known for some time already that it is possible to increase the electrical conductivity of polymers like Mylar, PPS and Kapton by several orders of magnitude by implanting different ions (argon, nitrogen, etc.). It is also possible to increase the hardness of Kapton, Mylar, PTFE (Teflon) etc. by implanting for example boron, nitrogen, carbon [51]. Implantation was especially successful for Kapton, where triple implantation of boron, nitrogen and carbon yielded a 30 times increase in hardness, resulting in a hardness three times the one which is typically obtainable for stainless steel.

Another well known application is the possibility of improving the performance of artificial hip joints by implanting the metal ball fitting into the polymeric (ultrahigh molecular weight polyethylene) cup. Implanting the metal part gave a reduction in wear of both the metal part and the polymeric cup. It has recently been shown in laboratory tests [52] that it is possible to obtain similar wear improvements by implanting low dose nitrogen into the polymeric part. It is expected that the effect is obtained by a hardening of the polymer. But perhaps an even more important effect is the changing of the wettability of the polymer surface. This improves the lubrication of the metal and polymer parts rubbing against each other.

9. Conclusions

Ion beam based technologies clearly have a place in the long list of surface treatment processes used for surface treatment and modification of industrial components. However, for the ion beam techniques to be widely accepted they need to be both readily available and to prove their advantages over existing technologies. To obtain this, it is necessary to continue developing the equipment to further improve its effectiveness, and it is necessary to improve the understanding of the mechanisms taking place by ion surface engineering and the tribological behaviour of these surfaces. It is also very important to carry out broad industrial testing and development of industrially acceptable quality assurance tests.

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