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PRACTICAL APPLICATIONS OF ION IMPLANTATION FOR TRIBOLOGICAL MODIFICATION OF SURFACES*

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Summary

Ion implantation of several different types of components and materials has been performed on a new generation high current implanter to obtain tribological improvements in the material surfaces. The accelerator is located at the recently formed Aarhus Tribology Centre. The accelerator is designed for research and development work as well as for implantation of components for industry on a commercial basis. The implanted tools are used in normal production in industry and the results obtained show that typically the component's lifetime is increased from two to six times.

1. Introduction

The use of ion implantation as a process to modify tribological surface properties of materials has recently become important; although, the process has been used for several years on an industrial scale in the semiconductor industry. The first use of ion implantation to improve the tribological performance of tools was at the beginning of the 1970s at the Atomic Energy Research Establishment, Harwell, U.K. Now it seems that the application of ion beams to non-semiconductors is ready for full-scale industrial exploitation.

The aim of this paper is to give a short description of the ion implantation process, the Aarhus high current ion accelerator and the Tribology Centre, and also to discuss some of the successful industrial applications of ion implantation performed with the Aarhus accelerator.

2. Ion implantation

In ion implantation, the surfaces to be treated are bombarded with high energy (50 - 200 keV) ions. The ions penetrate the surface and are typically

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stopped within the first 0.5 μm or less below the surface. The ions will be distributed from the surface to a maximum depth, with a maximum concentration in between. The maximum concentration of the implanted ions can be as high as 40 - 50 at.%.

Since it is possible using ion implantation to mix elements independent of diffusion constants and solid solubility values, it is in principle possible to create exactly the surface alloy desired by implanting the correct ions. The implanted ions cause physical and chemical changes in the material, which may lead to new, improved surface properties with respect to friction, wear, corrosion and fatigue. Ion implantation is not a coating process: the outer part of the original material is fundamentally altered. Thus there is no risk of a surface layer peeling off and there can be no change in dimensions in the treated parts. Since the implantation process can be performed at low temperatures (below 200 °C), the treated components are not distorted. Only the outermost layer is changed, leaving the bulk properties unaffected.

3. The Danfysik 1090-200 high current implanter

The ion implantation process is performed with accelerators. To obtain general industrial acceptance of ion implantation there must be efficient and versatile ion accelerators available. The majority of high current accelerators used commercially for ion implantation of tools *etc.* are capable only of implanting nitrogen or other ions from pure gaseous materials. With these accelerators it is thus not possible to implant metal ions.

In cooperation with the Institute of Physics, University of Aarhus and the Jutland Technological Institute, Aarhus, the Danish company Danfysik A/S has developed a new high current ion implanter (model Danfysik 1090-200 high current implanter) that will be capable of producing mass-analysed ion beam currents of up to 10 mA for virtually any element. Singly charged ions can be accelerated to energies of 200 keV. The accelerator is shown in Fig. 1. The components to be treated are placed in the 600 mm × 600 mm × 700 mm target chamber (see Fig. 3). Since ion implantation is a vacuum process the target chamber has to be pumped down to about 10^{-5} Torr before the treatment can be started. On the 1090-200 accelerator it is possible to evacuate the chamber to the vacuum required in less than 20 min unless there is considerable outgassing from the components to be treated.

The components to be implanted are mounted on a computer-controlled target manipulator that can rotate, tilt and move the components up and down during implantation (see Figs. 2 and 3). Without limiting the movements of the target holder and manipulator it is also possible to cool the components during implantation *via* water cooling of the holder system. During implantation the kinetic energy of the ions impinging on the material surface is dissipated as heat. With a beam current of 10 mA and an ion energy of 200 keV, the dissipated energy can be as high as 2 kW. The water cooling system has proved to be efficient in preventing overheating of the

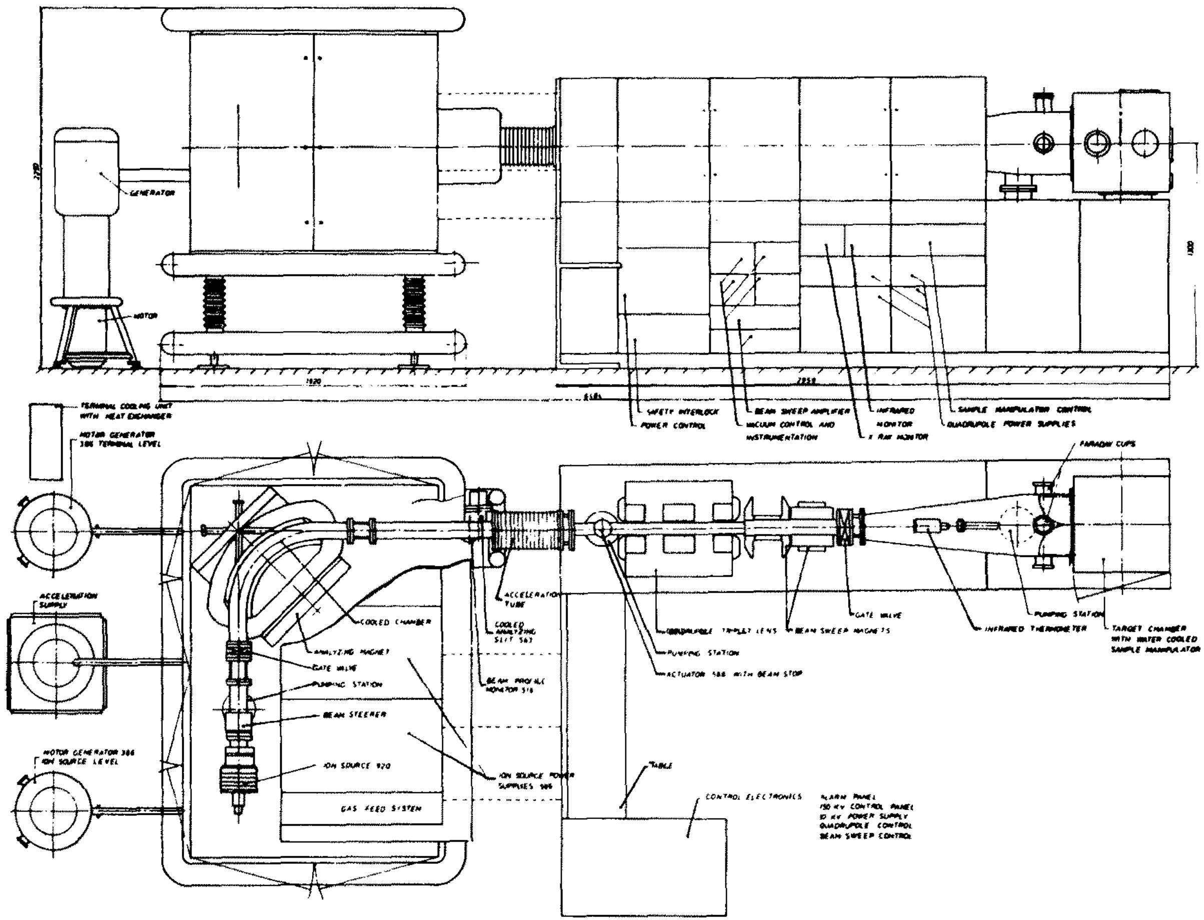


Fig. 1. The Danfysik 1090-200 high current implanter.

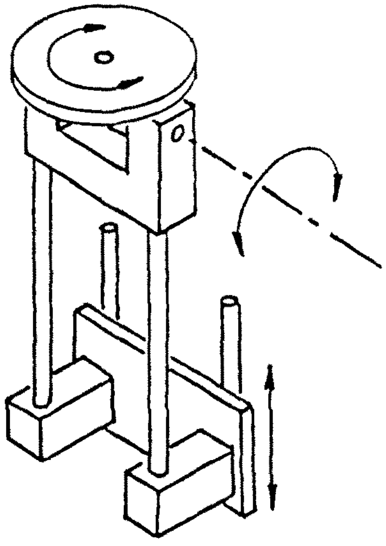


Fig. 2. Sketch of target manipulator.

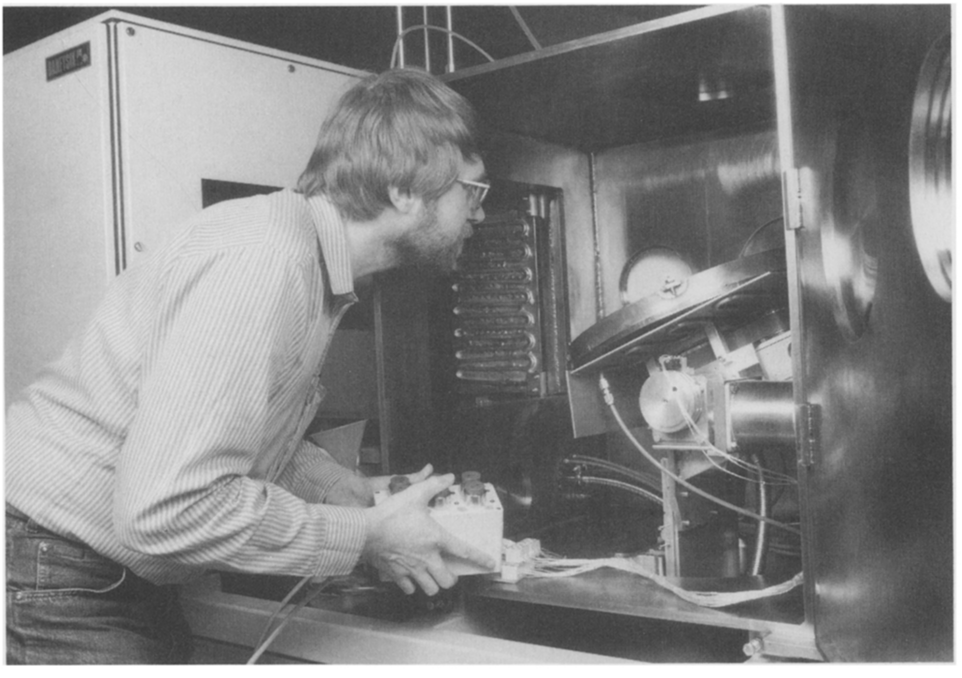


Fig. 3. A view into the target chamber showing part of the target manipulator and holder system. The manipulator can be controlled manually or by computer.

components during implantation. To ensure that overheating cannot occur the accelerator is equipped to measure continuously the temperature of the implanted surface during implantation and to interrupt the process automatically if a preset upper (or lower) limit is exceeded. The implantation process is automatically resumed as soon as the temperature is back within accepted limits.

Using a magnetic quadrupole triplet lens the ion beam can be focussed to a spot of any shape from circular to linear. The beam spot can be scanned in both the X and Y directions, covering an area of up to 40 cm $\times$ 40 cm or as low as 2 cm^2. Combined with the target manipulator it is therefore possible to implant successfully both small and large components of complicated shapes in a controlled and reproducible manner.

Under optimum conditions the implantation time with this accelerator can be as short as 10 s cm^{-2}, several orders of magnitude faster than with pure research accelerators.

4. The Aarhus Tribology Centre

The accelerator is installed at the newly formed Aarhus Tribology Centre at the Jutland Technological Institute, Aarhus, Denmark. The Tribology Centre is a cooperative venture between this institute, the Institute of Physics, University of Aarhus and Danfysik A/S. The aim of the Tribology Centre is to transfer ion implantation techniques for surface modification to industry by offering ion implantation services. At the same time it aims to develop implantation techniques and process hardware in collaboration with all the partners. Research work on ion implantation as a tool to obtain improved tribological surfaces has been carried out at the University of Aarhus for several years.

5. Case studies

Before implanting a wear component, the optimum implantation parameters for the material and the wear situation should be found. Some of the parameters and the following: the type of energy and dose of the ion, the temperature of the component during implantation and possibly also the pressure in the target chamber during implantation. In many cases it is not easy to calculate the optimum conditions, but fortunately the theoretical understanding of the process is increasing. With the growing use of ion implantation on industrial components, it is becoming possible in an increasing number of situations to find similar cases that have already been tested in laboratories or better still in production environments.

The first implantations of industrial production tools with the high current implanter were performed in January 1988. Since then, several different types of components and steels have been implanted. Many of these tools are still being tested in production and final results are available for only a limited number of cases. Some of the successful applications that have already been documented will be presented below. In all cases the tools have been implanted with nitrogen ions. Implantation of nitrogen in material surfaces to obtain improved tribological properties is the best documented implantation process.

5.1. Example 1

The materials tested were six taps (6 mm) of 1.3243 steel (AISI M35) (Fig. 4). The taps were implanted with 200 keV N_2^+ ions to a dose of 2×10^{17} N^+ ions cm^{-2}.

All six taps were tested in production in a set of six and the test was stopped when the first of the taps was worn out. The improvement obtained in this way was a fourfold increase in lifetime.

5.2. Example 2

One tap (10 mm) of K945 steel (AISI M7) was tested. This tap was implanted with 100 keV N^+ ions to a dose of 3×10^{17} N^+ ions cm^{-2}.

A doubling of the normal lifetime before resharpening was obtained on this tap. After resharpening the tap still showed a doubling of the lifetime. This indicates that perhaps the improvement derives not so much from a change in the cutting edges, but from a lowering in the adhesion or friction for the cut-off metal debris in the spaces between the cutters.

A tap exactly like the ion-implanted tap was coated using physical vapour deposition with a TiN layer. It was also tested on the same material and a similar improvement was obtained.

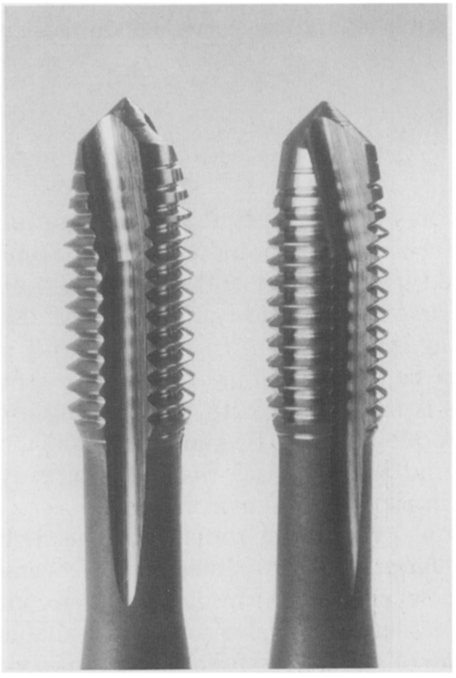


Fig. 4. Ion-implanted taps.

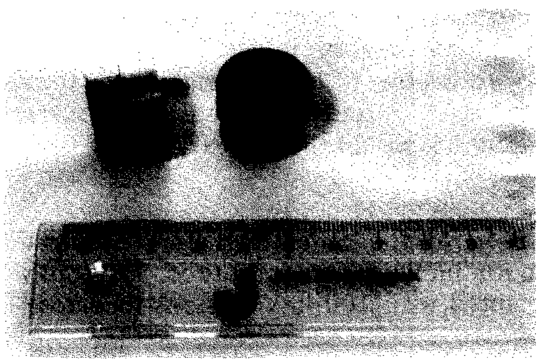
5.3. Example 3

One punch, cylinder, 1 cm in diameter, Sverker 3 (AISI D6) was tested. The punch was used to cut out rubber disks containing hard, abrasive TiO_2 particles. Before implantation the punch was hardened to 51 HRC (annealed at 550 °C). It was implanted with 100 keV N^+ ions to a dose of 3×10^{17} N^+ ions cm^{-2}.

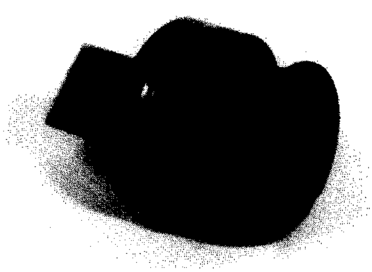
Compared with an unimplanted punch a sixfold improvement in lifetime was obtained. The punch was not tested after grinding. Earlier results indicate, however, that the improvement is not obtained on the punch end but on the punch sides. It is thus expected that the improved performance will continue after grinding.

5.4. Example 4

Figure 5 illustrates the testing material which is a pair of rolls for manipulating steel rods. The rolls rotate with rods clamped between them. In some cases a rod has to be stopped while the rolls are still rotating. This



(a)



(b)

Fig. 5. Ion-implanted rolls for manipulating steel rods. The two rolls (a) are new. The roll (b) has been worn out.

can cause serious wear of the rolls and result in expensive downtime for the machine in which they are working.

The rolls tested were made of UHB ORVAR 2M (AISI H13, 1.2344). They were hardened and gas nitrided. Afterwards they were implanted with 100 keV N^+ ions to a dose of 4×10^{17} N^+ ions cm^{-2}. The lifetimes of both rolls were increased by a factor of five. From the material composition it could be expected that an even better result could be obtained by implanting boron ions instead of nitrogen ions [1].

5.5. *Example 5*

Four dental tools (ultrasound tooth cleaners) were tested (Fig. 6). The dental tools were made of a titanium alloy. They were implanted with 100 keV N^+ ions to a dose of 5×10^{17} N^+ ions cm^{-2}. The lifetimes of the tools were doubled.

5.6. *Example 6*

A tool for shaping plastic using ultrasound was tested. The tool was made of Ti–6Al–4V and was implanted with 100 keV N^+ ions to a dose of 3×10^{17} N^+ ions cm^{-2}.

A final evaluation of the improved wear resistance was not possible since the tool was broken by misuse before it was worn out. The unimplanted tool does however leave a coating of the material on the formed plastic. The implanted tool left no material on the formed plastic surfaces and a marked improvement in the tool life would thus be expected.

5.7. *Example 7*

A die for the final calibration of the outer diameter of extruded aluminium tubes was subjected to ion implantation and tested. The tool was made of WC–6%Co and was implanted with 100 keV N^+ ions to a dose of

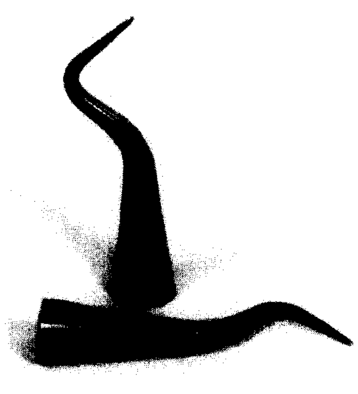


Fig. 6. Ion-implanted tooth cleaners (ultrasound).

1.5×10^{17} N^+ ions cm^{-2}. The temperature of the die was maintained between 200 and 450 °C during implantation.

The implanted die was in use for 5 months. The normal lifetime for an unimplanted die is 3 months.

5.8. Example 8

The test material was a blanking die for press cutting parts of tin cans. The tool was made of UHB GRANE steel and was implanted with 100 keV N^+ ions to a dose of 2×10^{17} N^+ ions cm^{-2}. During implantation the tool temperature was kept below 200 °C.

Depending on the worked tin material, the lifetime of the die will vary between 14 days and 2 months. The implanted die has until now worked for around 3 months.

5.9. Example 9

Seven reamer segments for reaming steel were tested. The reamers were made of 1.3342 steel (AISI M2). They were implanted with 100 keV N^+ ions to a dose of 2×10^{17} N^+ ions cm^{-2}. During implantation the temperature of the tool was kept below 230 °C.

The tool life was doubled by implantation. By implanting twice as many ions it will probably be possible to obtain an increase in tool life of up to six times [2].

5.10. Example 10

Four pairs of rotating dies for extrusion of plastic nets were tested (Fig. 7). The dies were made of SKF 356A steel (1.6582, AISI 4340). Before

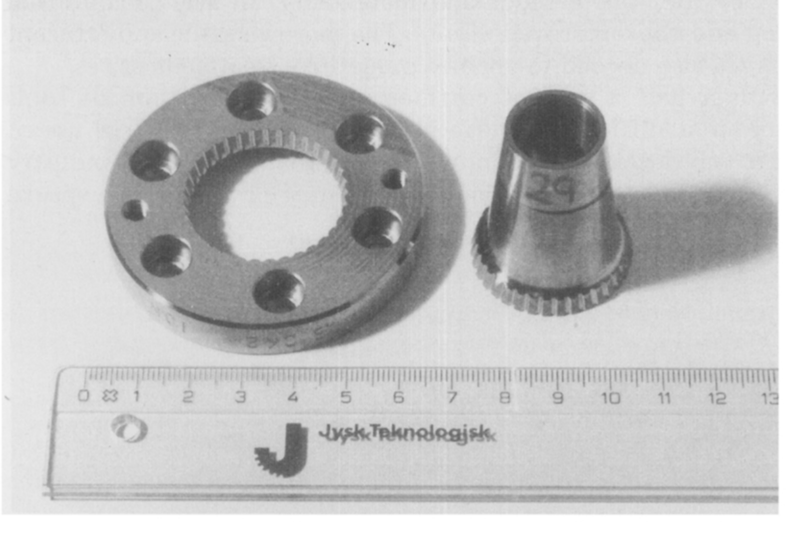


Fig. 7. Ion-implanted pair of dies for extrusion of plastic nets.

implantation the dies were gas nitrided. The dies were implanted with 100 keV N^+ ions to a dose of 3×10^{17} N^+ ions cm^{-2}. During implantation the temperature was kept below 200 °C.

Until now only one pair of the dies has been in use and final results for this set are not yet available. Preliminary results indicate, however, that a reduction in both friction and wear has been obtained. Wear and friction occurs on the counterparts when they are pressed together and rotated with respect to each other.

Several other tools for wood-cutting, paper-cutting, metal forming–bending, polymer processing and so on have been implanted and are now being tested in production. The preliminary results look very promising in several cases.

6. Conclusions

The present results show that although ion implantation changes only the outermost thin surface layer of a component it can in several cases improve the wear resistance of tools *etc.* working in production environments.

The effective lifetime improvement factor can be influenced by a large number of parameters. Furthermore, the present results represent only a few cases. Significantly better results are expected when more data and details of further applications become available, and the influencing implantation parameters can be finely tuned to the specific materials and applications. There is still a lack of detailed data on practical applications, and therefore the true potential of this technology has yet to be evaluated. The advent of new generation high current ion implanters such as the Danfysik 1090-200 for both gaseous and metal ions can lead to improved parameter tuning and thus improved results. The more versatile and efficient new accelerators are also needed to enable competitive treatment prices.

After less than half a year of commercial ion implantation of tools *etc.* for industry, it is difficult to judge in detail how the industrial use of ion implantation will develop. Until now it seems that the Danish industry in general has responded favourably and high volume production in special niches can be expected.

References

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