ELSEVIER

Nuclear Instruments and Methods in Physics Research B 113 (1996) 161-166

NIM B
Beam Interactions with Materials & Atoms

# Application of ion implantation in tooling industry

Christen A. Straede

*Tribology Centre, DTI Industry, Danish Technological Institute, Teknologiparken, DK-8000 Aarhus C, Denmark*

**Abstract**

In papers published during the last half of the 1980s it is often stated that the application of ion beams to non-semiconductor purposes seems ready for full-scale industrial exploitation. However, progress with respect to commercialisation of ion implantation has been slower than predicted, although the process is quite clearly building up niche markets, especially in the tooling industry. It is the main purpose of this paper to discuss the implementation of the process in the tooling market, and to describe strategies used to ensure its success. The basic idea has been to find niches where ion implantation out-performs other processes both technically and in prices. For instance, it has been clearly realised that one should avoid competing with physical vapour deposition or other coating techniques in market areas where they perform excellently, and instead find niches where the advantages of the ion implantation technique can be fully utilised. The paper will present typical case stories in order to illustrate market niches where the technique has its greatest successes and potential.

## 1. Introduction

Almost seven years ago it was stated that "Now it seems that the application of ion beams to non-semiconductor purposes is ready for full-scale industrial exploitation [1]". Despite the optimistic forecast, commercialisation of the process has been relatively moderate in Europe. Compared to the PVD (Physical Vapour Deposition) and CVD (Chemical Vapour Deposition) techniques ion implantation has not yet succeeded in gaining similarly sized markets in the tooling industry.

Although commercialisation of ion implantation on tools has been relatively successful in Denmark when compared to many other countries, the progress has not been as fast and as pronounced as expected.

## 2. Background

In 1985 the Danish Technological Institute (DTI) in Aarhus, Denmark decided to set up a Centre working with tribology in general and to focus on the implementation of ion implantation in industry.

The background to this decision was the pioneering work in that area which, inspired by Harwell, UK [2], was performed at the University of Aarhus, Denmark in the 1970s and the beginning of the 1980s. The implantation facilities at Aarhus University allowed the demonstration implantation of single and small tools only, showing the technical feasibility of the process. From this, a reasonable amount of interest was initiated from Danish industry.

The global state-of-the-art in commercial non-semiconductor ion implantation was investigated and available equipment suitable for performing commercial implantation was identified. On the basis of this, general specifications were defined for what the author of this paper, at that time, considered to be an optimum process equipment. The equipment should have:

- a versatile ion source,
- a range of ion energy between 50–200 keV,
- an analysing magnet (before post-acceleration),
- a 600 mm × 600 mm × 600 mm process chamber or a ball-shaped chamber of similar size,
- possibilities of extending the chamber,
- possibility of focusing/defocusing and scanning the beam,
- a manipulation table, able to manipulate 50 kg,
- a pump-down time for process chamber of maximum 15 minutes,
- an on-line monitoring of tool temperature during implantation,
- a possibility of computer control of tool and beam manipulation.

These and more requirements were presented to several companies around the world. On the basis of this, a contract with Danfysik was signed in 1986 and the prototype of the Danfysik 1090-200 implanter was constructed [3], Fig. 1.

The accelerator was installed at the DTI in November 1987, and the first commercial job was performed in January 1988. Even while the implanter was being built, much effort was made to market the process, and an information campaign aimed at industry was initiated.


*SSDI* 0168-583X(95)01380-6

## 3. Marketing in Denmark

### *3.1. Introduction to small companies*

The marketing was based on talks, meetings and articles in newspapers and journals aimed at industry. Most companies, especially the relatively small ones (less than 50 employees) showed a positive response to the campaign and wanted to get more information on the process, or even to pay for trial implantations. However, it was very difficult to get the larger companies interested at the beginning.

### *3.2. Networks and industrial collaborations*

One way of making it known to Danish industry that ion implantation was a process they could benefit from, was via TICs (Technological Information Centres). In every county in Denmark there is a TIC. The role of the TIC's is to communicate news of technological developments to small and medium sized local companies. The TIC's know these companies, their needs and problems, and often they have many good personal contacts in the companies. Together with TIC employees, visits to small and medium sized companies all around Denmark were initiated. Thus, the first contacts with companies were made relatively easily and a lot of scepticism from the companies was avoided. As a result of this, several trial implantations were made, and the experience gained helped improve the success rate substantially. Years later the large companies realised the success of several small companies, and today an important part of the work is performed for large companies.

To facilitate co-operation between universities, organisations like DTI, and industry, a Centre for Surface Technology – Dry Coating Processes was established in 1989 with the following fields of activity: Ion implantation, PVD, CVD, plasma CVD including diamond and diamond-like carbon coatings, and tribology in general. Research and development work in Denmark in this field was supported and efforts were made to implement new processes in Danish industry. The participating companies in this centre played a very active part in the research and development work, e.g., by carrying out large numbers of field tests. This type of collaboration is being continued with a substantially increased number of industrial establishments, both small and large, in the Danish Materials Development Programme (MUP II). These types of collaboration have provided an important and direct channel of information to several companies. By being able to offer a broad spectrum of surface treatments the Tribology Centre is now in touch with a very large number of companies, which enhances dissemination of the ion implantation technique.

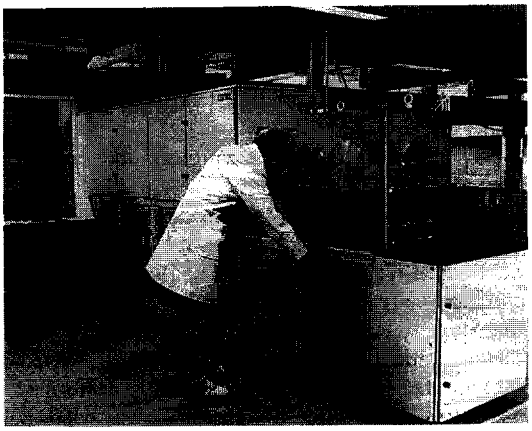

Fig. 1. The Danfysik 1090-200 ion implanter at the DTI Tribology Centre.

Furthermore, ion implantation is recommended to customers only when it is the best solution. This gives better credibility to the process, which by many customers may be considered rather "exotic" due to the shallow and invisible implanted layer. The Tribology Centre has found it necessary in order to be able to promote ion implantation in the best possible way to have substantial knowledge in the areas of ion implantation, PVD, CVD, plasma CVD, tribology in general, tooling, metallurgy, and a general knowledge of industrial production processes and problems. The DTI Tribology Centre also started research and development and commercial job coating with PVD in 1992 and plasma CVD (PCVD) on a relatively large scale in 1994.

### *3.3. Ion implantation as a relatively cheap surface treatment based on selected area implantation*

Ion implantation has often been claimed to be expensive. However, by using an implanter with an advanced ion beam steering and focusing facility it is only necessary to treat critical areas. Such vital areas of large tools can often be relatively small. In many cases, this will reduce the process time and consequently facilitate lowering of the price. Market acceptance in Denmark has been greatly influenced by this because it was thus possible to find niche tooling areas where ion implantation can compete with processes like PVD and CVD both technically and price-wise.

A hollow cylindrical punch for tin-can production is an example of the advantage of using advanced beam control and steering on the ion implanter. At the DTI Tribology Centre, such tools are frequently ion implanted and although they often are relatively large (diameters up to 30–40 cm), they can be implanted in a short time and the treatment can be relatively cheap. This is due to the fact that the critical area near the cutting or bending edge is relatively small and by implanting this area only, the process time is greatly reduced.

For the above-mentioned punch (diameter 20 cm) the critical area that must be optimally and homogeneously implanted is about 63 $cm^2$. Such a tool is implanted by directing a focused beam (beam diameter about ≈ 1 cm, horizontally fixed and scanned 2 cm in the vertical direction) towards the centre of the critical area on the rotating tool and with the rotational axis held 45° from vertical.

Several such tools can be mounted in one batch where the PC controlled ion beam shifts frequently from tool to tool [4]. If, for instance, three punches are implanted in one batch, the total area to be implanted is about 3 × 63 $cm^2$ (homogeneously implanted) plus 3 × 63 $cm^2$ (area of "wasted beam") in total 378 $cm^2$. With a beam current of 4 mA $N^+$, the typical process time is about 1.5–3 hours for the whole batch, and each tool is only subjected to about 100 W of beam power. Cooling the tools through the water-cooled tool manipulator is therefore easy, even with simple fixtures.

If, instead, the same batch of tools is to be implanted without "selected area implantation" but using a broad stationary beam, the situation becomes quite different. In the present case, a broad stationary beam would require a diameter of about ≈ 45 cm with a beam area of about 1590 $cm^2$. Due to the rotation of the target, the net area to be implanted is 1590 $cm^2 \times \pi = 4995$ $cm^2$. This area is 4995/378 ≈ 13 times larger than the total implanted area

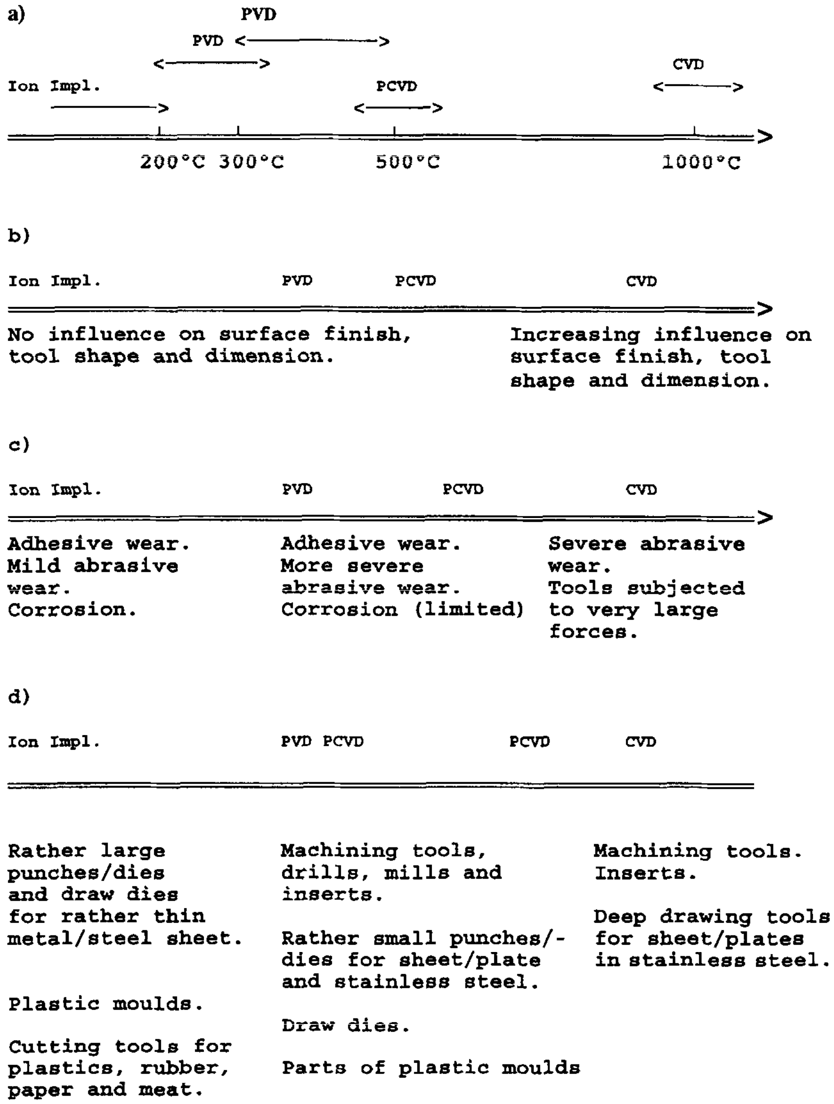


Fig. 2. Comparisons between different surface treatments. (a) Process temperatures. (b) Influence from the surface treatment on surface finish, tool shape and dimension. (c) Capability of reducing wear. (d) Typical examples of various applications in Denmark. At present PCVD is very new on the commercial market and the use of the process is still limited in Denmark. However, estimates of some of the potential applications of the treatment are shown.

in the "selected area" approach. In this case, a beam current of $13 \times 4$ mA = 52 mA is needed for the process time to be of the order of 1.5–3 hours. For such a beam current, each tool is subjected to about 1000–1500 W. Thus, cooling the tools during the process may be very difficult or even impossible. In addition, running an ion source and an accelerator with a 52 mA beam instead of a 4 mA beam is often more troublesome and demands more servicing and refurbishment of the equipment.

The "selected area implantation" technique will often result in a productivity gain of about ten times and a corresponding lower cost of ion implantation. Furthermore, the "selected area implantation" is something that, to the customer, strongly and in many cases very positively separates ion implantation from competing processes like PVD or CVD where it can be difficult and certainly expensive to make selected area treatment.

If an implanter of the "broadbeam, non-scanned beam and very high-current beam" type is used, other tool types will probably be the "best choice" for ion implantation with respect to the ability to perform the treatment at a competitive price.

## 4. Important points to consider when marketing ion implantation

### 4.1. Technical considerations

It is of major importance to clearly identify whether the problem is adhesive, fatigue or abrasive wear or perhaps corrosion. The problem may be connected with bulk properties rather than due to surface problems. The tool (or wear part) material must be identified as well as the work material, and hardening procedures and tempering temperature must be known. However, the surface treater must always be aware that information given by the customer may not be correct. It is often necessary to investigate the problem, inspect a worn tool or perhaps even to see the production. Failure to clearly identify the problem creates a considerable risk of producing an unsuccessful ion implantation with the result of losing a (potential) customer.

Generally, it also is very important to give the customer some basic knowledge of how to handle ion implanted surfaces. For instance, polishing or other preparation methods for the surface treated tool before it is put into production can, of course, destroy the ion implanted surface layer on the tool.

### 4.2. Tactical and strategic considerations

It is very important to find niche areas where ion implantation can out-perform other surface treatments with respect to technical performance or price (see Sections 6 and 7 and Fig. 2).

It is a good sales argument that there is practically no risk involved in having a tool ion implanted. The chance of negative effects is negligible, and for instance companies using expensive and delicate tools for plastic moulding often find this very important.

Finally it may be beneficial to show the customer financial calculations on the increased gain or turnover by using surface treated tools. If the tools are surface treated and therefore last longer or enable faster production, it very often turns out that the price of surface treatment is less than 5–10% of the expected gain.

## 5. Ion implantation compared to PVD, CVD and PCVD

Ion implanted, PVD, CVD and PCVD treated surfaces possess quite different properties, and the treatments are performed at different process temperatures. Each treatment has its advantages and disadvantages and each has its particular fields of application.

CVD coating of tools and components gives a wear resistant surface layer normally made of 3–10 μm thick TiN and TiC [5]. Because of the high process temperature (about 1000°C) thermal diffusion results in a mixed interface between coating and substrate giving a very good adhesion between coating and substrate. For tools made of hardened steel, new hardening and tempering procedures must be applied after the CVD process due to the high process temperature. Thus, alteration of tool shape and dimensions must be taken into account, as well as some alteration of the surface finish by increased roughness.

PCVD is a relatively new way of producing CVD coatings at lower process temperatures [6]. The process is very similar to standard CVD processes, but due to the presence of a plasma the parts to be coated need only be heated to around 450–550°C. The typical coatings produced are the same as standard CVD. PCVD processes are also used to produce diamond and diamond-like carbon (DLC) coatings.

PVD is a common denomination for several different but somewhat similar processes where tools and components are coated with wear resistant layers typically made of 2–3 μm thick TiN, TiAlN, TiCN, or CrN [7–9]. The process temperature is typically between 300 and 500°C depending on the type of PVD. PVD coatings do not have an intermixed interface as mentioned for CVD. The adhesion of PVD coatings can therefore often be a limiting factor when compared to CVD.

In Denmark surface treatment of machining tools like drills, mills and inserts is primarily made by PVD or PCVD/CVD. In most cases such tools are subjected to rather severe wear, and in such cases ion implantation may not be the most efficient treatment when compared to PVD and PCVD/CVD, due to the shallow depth of the implanted layer. However, there are exceptions to this, but due to the relatively small dimensions of such machining tools it is often difficult to perform ion implantation on selected areas of these tools, which makes ion implantation relatively expensive in these cases.

A rough comparison of the different treatments, a kind of ranking between them is given in Fig. 2. The figure should only be used as a rough guide, and in several cases there are exceptions to the shown ranking and classification. However, put in general terms, ion implantation is a very gentle and safe treatment especially suited for delicate tools. However, when dealing with more severe wear situations, the shallow depth of the implanted layer may be a limiting factor to the use of ion implantation.

In many applications, however, where tools are subjected to adhesive and/or mild abrasive wear, the treatment has proved to be second to none, also price-wise.

## 6. Commercial ion implantation

Ion implantation has too often been introduced in areas where it has been technically inferior or quite expensive compared to competing treatments. This gives a bad reputation to the technique. However, there are now some (less than ten) establishments/companies in Europe which to the author's present knowledge actively offer commercial ion implantation in the non-semiconductor area.

Many companies in Denmark have now obtained significant benefits from ion implantation and are regularly using ion implantation as a standard process. The technique has been marketed and most successfully implemented in tool areas where it is possible to utilise the specific advantages the technique offers, e.g. for the following tool types:

- Tools tempered at low temperatures (e.g. below 200°C).
- Precision tools whose shape may be altered by heating.
- Highly polished tools.
- Tools where (in spite of the enhanced life) refurbishment should still be possible/easy.

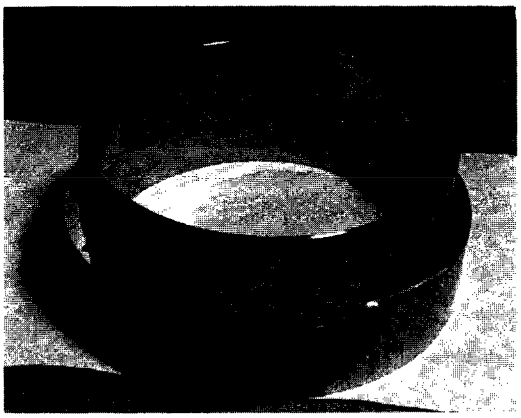

Fig. 3. Ion implantation is used extensively in the packing industry to improve the life of production tools.

- Very expensive tools since the risk of negative effects is very small.
- Rather large tools on which the wear area is relatively small.

Today thousands of tools and tool parts are implanted at the DTI Tribology Centre each year, and at several tool makers' ion implantation has become an integral part of their specifications just like steel type and thermal hardening procedures. Most of these tools are delicate and rather large punching/bending and drawing tools for thin metal sheets and plastic injection moulds. To some extent commercial ion implantation is also performed on cutting tools for paper, meat and rubber and the potential market in this area is considered to be substantial.

In order to illustrate the typical tool areas some examples of improved tool performance by ion implantation are shown below. The results have all been obtained in real-life production.

## 7. Examples of improved production tools

### *7.1. Punching / forming metal sheets*

- Forming/cutting punches and dies working very thin sheets or tin-can material, see Fig. 3. The tool material is mostly AISI D2, Vanadis 4 (Uddeholm) steel, AISI A2 and AISI M3 steel. Tool failure is caused by seizing and mild abrasive wear. The tools are delicate high tolerance tools, most of which are rather large. They are implanted locally on the critical areas with nitrogen ions. As a result of ion implantation the tools last five to ten times longer or even more. Although extended tool life is obtained, resharpening of the punches/dies may in some cases be necessary. However, resharpening is normally done from the top, and the implanted layer on the punch/die sides is left untouched. The companies have observed that extended tool life is still obtained after several resharpening operations.
- Knives made of AISI D2 steel for shearing/cutting aluminium. Material pick-up would stop the production at 80000 cuts. After implantation the tool can make up to 800000 cuts before repolishing is needed.
- CrN-PVD coated punches for punching aluminium. $N^+$ implantation results in reduced adhesive wear, and the consumption of lubricants is reduced. Tool life is enhanced about ten times when compared to CrN coating alone.
- TiN–PVD coated punches for forming sheet metal. $C^+$ implantation results in reduced friction and improved slide of the work material.

### *7.2. Plastic forming*

- TiN coated steel parts for plastic moulds. $N^+$ implantation improves the slip of the plastics.

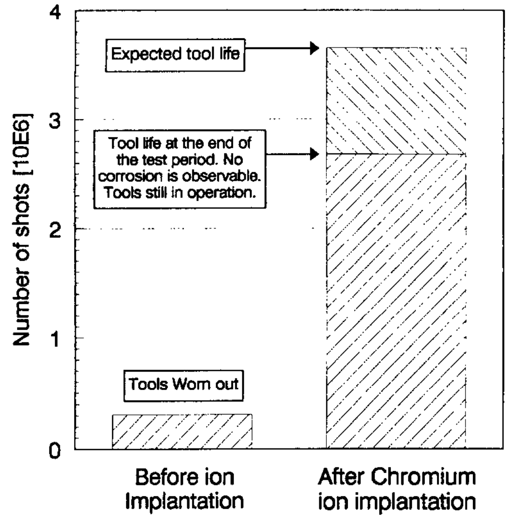


Fig. 4. Injection moulds from LEGO System Ltd are subjected to corrosive wear at the air outlets. In this case, tool life is increased by about 12–13 times by $Cr^+$ implantation. In another case (not shown here) nitrogen implantation of gates in injection mounds resulted in reduced abrasive wear and tool life was enhanced by 3.5 times.

- An example from LEGO System Ltd. In Fig. 4 are shown field test results from plastic moulds which are subjected to corrosive attack near the air outlets. During the process the plastic emits aggressive gases which attack the hardened steel moulds locally at the air outlets. The life of injection moulds which are subjected to corrosive attack can be enhanced by $Cr^+$ implantation at the air outlets, typically by three to four times. However, in the present example tool life is enhanced by as much as 12–13 times by chromium ion implantation.

### 7.3. Other work materials

- Steel knives for cutting meat. $N^+$ implantation results in life improvement by a factor of four to five.
- Precision knives for cutting plastic/paper labels. $N^+$ implantation gives marked improvement in performance and higher product quality.
- Knives for cutting rubber. $N^+$ implantation results in seven times life improvement.

## 8. Conclusion

Ion implantation has proved to be a commercially feasible surface treatment of production tools. By using the specific advantages of the technique, ion implantation has been successfully introduced as a second to none commercial surface treatment of several tool types. Today, ion implantation does therefore play an important role in commercial surface treatment of tools, and has found a large and increasing number of application niches on the tool market. However, with a highly focused marketing campaign aiming at the right niche areas and based on an understanding of industrial mechanisms, there is a much larger market to be gained.

It is believed that ion implantation has an important and relatively large market potential in Europe, where an increasing number of industries may benefit greatly from the technique. It is important to find, to build up and to focus on the relevant niches for the process, and not try to compete with other surface treatments in areas where ion implantation is not the best choice. It is expected that the most successful commercialisation of ion implantation will take place at establishments also offering other surface treatments.

## Acknowledgements

This work has been supported by the EU, RA-372 SPRINT Project and the Danish Materials Technology Development Programme No. II (MUP II), Framework Programme for Low Temperature Surface Technology and Associated Minicentre for Nanotribology.

## References

[1] C.A. Straede, Wear 130 (1989) 113.
[2] G. Dearnaley and N.E.W. Hartley, Thin Solid Films 54 (1978) 215.
[3] B.R. Nielsen, P. Abrahamsen and S. Eriksen, Mater. Sci. Eng. A 116 (1989) 193.
[4] B. Torp, P. Abrahamsen, S. Eriksen and B.R. Nielsen, Surf. Coat. Technol. 51 (1992) 556.
[5] H.E. Rebenne and D.G. Bhat, Surf. Coat. Technol. 63 (1994) 1.
[6] K. Kawata, Surf. Coat. Technol. 54/55 (1992) 604.
[7] K. Reichelt and X. Jiang, Thin Solid Films 191 (1990) 91.
[8] T. Leyendecker, O. Lemmer, S. Esser and J. Ebberink, Surf. Coat. Technol. 48 (1991) 175.
[9] E.J. Bienk, H. Reitz and N.J. Mikkelsen, Surf. Coat. Technol. in press.