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Implementation of ion implantation in European industry

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Abstract

Commercialization of ion implantation in Europe has progressed more slowly than predicted, but ion implantation niche markets are clearly increasing, especially in the tooling industry. This paper discusses the commercialization of non-semiconductor ion implantation in the European market and in Denmark in particular.

The relatively successful commercialization of ion implantation in Denmark is discussed in relation to the situation in Europe, and features generally furthering commercialization of the process are described.

The main strategy in Denmark has been not to compete with PVD or other coating techniques in areas in which they perform excellently, but to find niches where ion implantation outperforms other processes both technically and economically. The appropriate design of the implanter facilitates the exploitation of the specific advantages of the ion implantation technique, generating a superior surface treatment method suitable for several important tool niches. Case histories are described, illustrating relevant market niches.

The specialist knowledge of atomic or nuclear physicists, although necessary, is not sufficient to commercialize non-semiconductor ion implantation. The physicist must move out of the laboratory to understand the various aspects of the tooling trade, and to acquire the ability to establish and maintain close contacts with industrial customers with sound knowledge of materials, tribology and tooling.

Keywords: Commercialization; Industry; Ion implantation; Tools

1. Introduction

Almost 7 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 this optimistic forecast, commercialization of the process has been relatively moderate in Europe. Unlike the physical vapour deposition (PVD) and chemical vapour deposition (CVD) techniques, ion implantation has not yet succeeded in gaining a vast market, not even in the tooling trade where the technique has a large potential. In Ref. [2], 3 years later, it was stated, still optimistically but perhaps a little more reluctantly, that "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".

In Denmark, the commercialization of ion implantation has been relatively successful compared with many other countries, but not as quickly or as pronounced as expected; this shows that, despite its many advantages, ion implantation can be rather hard to sell.

The reasons for the relatively large success in Denmark are discussed, and aspects of particular importance to the successful commercialization of the process are presented. In addition, commercial ion implantation is compared with competing or, more correctly, complementary surface treatment techniques such as PVD and CVD.

2. Background

In the 1970s and beginning of the 1980s, pioneering work in the area of ion implantation, inspired by workers at Harwell, UK [3], was performed at the University of Aarhus, Denmark. A reasonable amount of interest from Danish industry was initiated, and in 1985 the Danish Technological Institute (DTI), Aarhus, Denmark decided to set up a centre working with tribology in general and focusing on the implementation of ion implantation in industry.

The global state-of-the-art in commercial non-semiconductor ion implantation was investigated and available equipment suitable for performing commercial

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implantation was identified. On the basis of this, the general requirements for an optimum ion implantation machine were defined as follows:
(1) a versatile ion source;
(2) a range of ion energy between 50 and 300 keV;
(3) an analysing magnet (before post-acceleration);
(4) a process chamber (600 mm × 600 mm × 600 mm) or ball-shaped chamber of similar size;
(5) possibilities of extending the chamber;
(6) possibility of focusing/defocusing and scanning the beam;
(7) a manipulation table, able to manipulate 50 kg;
(8) a pump-down time for the process chamber of a maximum of 15 min;
(9) on-line monitoring of tool temperature during implantation;
(10) possibility of later extension with computer control of tool and beam manipulation.

A presentation of these and more requirements to companies all over the world resulted in a contract with Danfysik in March 1986. The prototype of the Danfysik 1090-200 implanter was built [4] on the basis of very constructive discussions between DTI and Danfysik.

The accelerator (Fig. 1) 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 placed into marketing the process, and an information campaign aimed at industry was initiated.

3. Marketing in Denmark

3.1. Introduction into small companies

The marketing included talks, meetings and articles in newspapers and journals aimed at industry. Many companies, especially the relatively small ones (less than 50 employees), responded positively to the campaign, requested further information or even paid for trial implantations, while large companies showed little interest at the beginning.

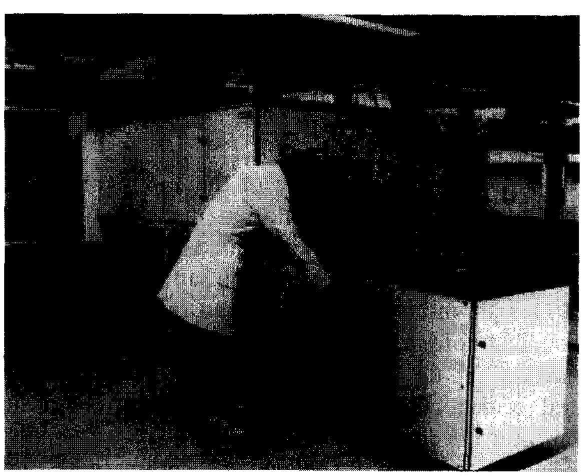

Fig. 1. The Danfysik 1090-200 ion implanter at the DTI Tribology Centre.

Initially, trial implantations were made on many different tool types chosen on the basis of reported successes in the UK and USA [3,5,6]. However, with a rather low success rate (below 25%), business progressed quite slowly.

3.2. Networks and industrial collaboration

Technological Information Centres (TICs) have been instrumental in the implementation of ion implantation in Denmark. TICs have been established in all parts of Denmark with the main role of communicating information about technological developments to the small- and medium-sized companies in their area. On the basis of their local knowledge, the TICs selected relevant companies to be visited by the TIC and DTI Tribology Centre. Introduction of the ion implantation process was met with less scepticism and much readier acceptance due to the presence of the local TIC representative.

As a result, many trial implantations were made, and the experience gained helped to improve the success rate substantially. Years later the large companies realized 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, organizations such as 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 (PCVD) 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).

The DTI Tribology Centre also takes part in an EU SPRINT campaign in which collaborators from Spain, UK and Denmark share knowledge and make joint efforts to market ion implantation in the industrial metallic sector [7].

Through these types of collaboration, a large number of companies have acquired an important and direct channel of information.

3.3. The effect of other surface treatments

Commercial job coating with PVD was established at the DTI Tribology Centre in 1992 and PCVD in 1994.

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.

Furthermore, ion implantation is recommended to customers only when it is the best solution. This gives better credibility to the process, which may be considered rather "exotic" by many customers due to the shallow and invisible implanted layer.

3.4. *The role of the physicist*

In most cases around the world, commercial ion implantation is introduced, managed and run mainly by physicists. This also used to apply to the DTI Tribology Centre. However, it should be taken into consideration that physicists may not have sufficient knowledge of metallurgy, tooling and industrial production and marketing processes, and this lack of knowledge may constitute a major problem in the commercialization of non-semiconductor ion implantation. Realizing this, the Tribology Centre has actively acquired knowledge in these areas and has also taken on new staff with the required knowledge, so that today the Tribology Centre has substantial knowledge in the areas of ion implantation, PVD, CVD, PCVD, tribology in general, tooling, metallurgy and general knowledge of industrial production processes and problems.

3.5. *Ion implantation as a relatively cheap surface treatment*

Ion implantation has often been claimed to be expensive. However, by utilizing the advanced ion beam steering and focusing possibilities of the implanter at the DTI Tribology Centre, implantation can be made on the critical areas only. In many cases, this reduces the process time and, consequently, facilitates a lowering of the price. Market acceptance in Denmark has been greatly influenced by this.

4. Important points to consider when marketing ion implantation

4.1. *An extensive campaign is needed*

Marketing ion implantation may need to be done differently in different countries. In Denmark, marketing through industrial networks and collaboration has proved a highly efficient method due to the many small- and medium-sized companies. In all countries, however, success is inevitably built on hard and continuous work, including innumerable talks and meetings, visits to companies, forwarding of a vast amount of information material and success stories in newspapers and journals.

4.2. *Technical considerations*

Implementing ion implantation is particularly difficult due to the fact that one category of tools benefits the most from the treatment. These are delicate tools subjected to relatively mild wear and usually producing hundreds of thousands of items. These tools will normally last for several weeks or months, and in many cases they are used in production in three shifts around the clock. For such tools, tool life can be enhanced by up to several months and even years by ion implantation, and thus they can produce millions of items. Companies using such tools find it quite hard to keep track of the field tests of implanted tools, especially because the treatment is invisible. For such companies, it may be difficult to obtain experience and results with ion implantation and its benefits. Marking ion implanted parts would greatly help this and enhance acceptance of the product.

It is of major importance to identify clearly whether the problem involves adhesive, fatigue or abrasive wear or perhaps corrosion. The problem may be connected with bulk properties rather than surface problems. The tool (or wear part) material must be identified as well as the work material, and the 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 identify the problem clearly creates a considerable risk of producing unsuccessful ion implantation with the result of losing a (potential) customer.

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

4.3. *Tactical and strategic considerations*

Many industrial customers do not realize that they have a specific problem. Many tool refurbishment/replacement routines and production standstills are considered standard procedures. Such industries will not become customers unless the marketing campaign includes a very active and relatively aggressive approach. It may be beneficial to ask direct questions about the frequency and cost of standstills, the frequency of refurbishments etc., which may make the customer realize that perhaps large (financial) improvements could be obtained by enhancing tool life. Improvements may be more convincing than problem solving. Information from industrial customers on their production methods should always be considered as strictly confidential. Otherwise, the customer or market may be lost.

It is very important to find niches in which ion implantation can outperform other surface treatments with respect to technical performance or price (see also Section 9). In addition, the process should mainly be marketed as an established and fully developed technique. Ion implantation is a product. It is necessary to target on applications in which the process has proved successful, and to test newly developed ion implantation processes and applications only in collaboration with companies with which good close relations are already established. When a test treatment is offered, it should always be made in agreement with the customer.

The negligible risk involved in having a tool ion implanted is another good sales argument, and companies using expensive and delicate tools for plastic moulding often find this important.

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

5. Commercial ion implantation in Europe

The relatively slow progress of commercial ion implantation in Europe may be explained, to some extent, by the lack of awareness of the above-mentioned points. Furthermore, ion implantation may have been introduced in areas in which it is technically inferior or quite expensive, which has given it a bad name.

Some of the establishments/companies in Europe which, at present, offer commercial ion implantation in the non-semiconductor area are research facilities. The companies and research institutes which are more commercially oriented include AEA Industrial Technology, TecVac and Tech-Ni-Plant (all UK), MAT (Germany), Nitruvid and IBS (both France), INASMET and AIN (both Spain) and the DTI Tribology Centre (Denmark). Others may also be emerging or present in the market, and the number of commercial jobs performed in the non-semiconductor field may vary with each establishment. In the future, the more successful establishments may be those which offer ion implantation in addition to other surface treatments.

6. Commercial ion implantation in Denmark

The ion implanter installed at DTI is the only one used for commercial jobs in Denmark at present. Despite the relative success in Denmark, the Danish market potential is considered to be much larger than the present market, and over the last few years the machine has been utilized for a steadily increasing number of commercial jobs. In addition to the extensive marketing campaign, continuous modification of the machine's commercial capabilities has made this possible.

Compared with many other commercial ion implanters, the Danfysik 1090-200 machine is relatively advanced. The machine is capable of performing selected area implantation and, in addition to gaseous ions such as nitrogen (N^+), the machine efficiently produces metallic ions, e.g. Cr^+.

Many Danish companies have now obtained significant improvements by ion implantation and are regular customers at the Tribology Centre. The technique has been marketed and most successfully implemented where it is possible to utilize its specific advantages, e.g. in the following tool areas:

(1) tools tempered at low temperatures (e.g. below 200 °C);
(2) precision tools whose shape may be altered by heating;
(3) highly polished tools;
(4) tools where (in spite of the enhanced life) refurbishment should still be possible/easy;
(5) very expensive tools since the risk of negative effects is very small;
(6) 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. However, the potential number of applications on such tools is considered to be much larger than the present use of the treatment.

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

7. Examples of improved production tools

7.1. *Punching/forming metal sheets*

(1) Forming/cutting punches and dies working very thin sheets or tin can material (see Fig. 2). 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

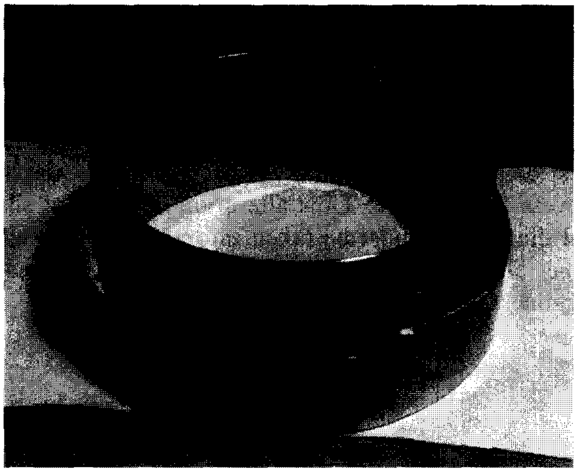

Fig. 2. Ion implantation is used extensively in the packing industry to improve the life of production tools. Tool life is enhanced by 5–10 times or more.

critical areas with nitrogen ions. As a result of ion implantation, the tools last 5–10 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.

(2) Drawing dies made of Vanadis 4 or AISI D2 steel. These tools work without lubrication on lacquered thin sheets. They are subjected to abrasive wear and, to some extent, seizing occurs. On average, the tools normally last around 3 weeks. After nitrogen implantation, tool life is increased to more than 6 months.
(3) Drawing ring made of AISI M2 steel for drawing very thin sheets of stainless steel. Without ion implantation, severe seizing takes place. After N^+ implantation, over 600 000 items can be drawn without problems.
(4) Steel punches made of AISI M2 steel for punching holes in aluminium. Without ion implantation, substantial amounts of adhesive wear and material pick-up are inevitable. N^+ implantation results in superior performance, reduced material pick-up and less use of lubricants.
(5) Knives made of AISI D2 steel for shearing/cutting aluminium. Material pick-up stops the production at 80 000 cuts. After implantation, the tool can make up to 800 000 cuts before repolishing is needed.
(6) 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 10 times when compared with CrN coating alone.
(7) TiN PVD-coated punches for forming sheet metal. C^+ implantation results in reduced friction and improved sliding of the work material.

7.2. Plastic forming

(1) TiN-coated steel parts for plastic moulds. N^+ implantation improves the slip of the plastics.
(2) An example from LEGO System Ltd. In Fig. 3, field test results from plastic moulds subjected to corrosive attack near the air outlets are shown. 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 3–4 times. However, in the present example, tool life is enhanced by as much as 12–13 times by chromium ion implantation.
(3) In another example from LEGO System Ltd., nitrogen implantation of gates in injection moulds results in reduced abrasive wear, and tool life is enhanced 3.5-fold.

7.3. Other work materials

(1) Steel knives for cutting meat. N^+ implantation results in life improvement by a factor of 4–5.
(2) Precision knives for cutting plastic/paper labels. N^+ implantation gives a marked improvement in performance and higher product quality.
(3) Knives for cutting rubber. N^+ implantation results in a sevenfold life improvement.
(4) Stainless steel knives for cutting foam rubber. N^+ implantation results in a threefold life improvement.

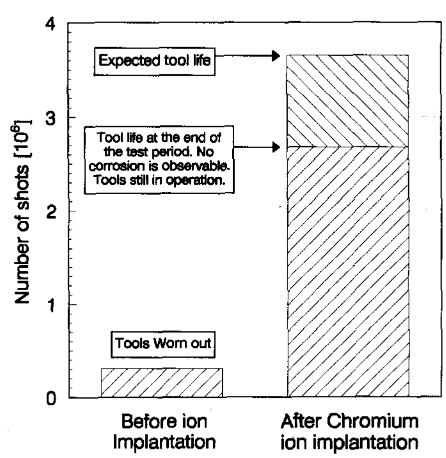

Fig. 3. Injection moulds from LEGO System Ltd. are subjected to corrosive wear at the air outlets. In this case, tool life is increased by about 12–13 times by Cr^+ implantation. In another case (not shown here), nitrogen implantation of gates in injection moulds results in reduced abrasive wear, and tool life is enhanced 3.5- fold.

8. Ion implantation compared with PVD, CVD and PCVD

Surfaces treated by ion implantation, PVD, CVD and PCVD 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 (3–10 μm thick) normally made of TiN and TiC [8]. Because of the high process temperature (about 1000 °C), thermal diffusion results in a mixed interface between the coating and the substrate giving very good adhesion. 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 the tool shape and dimensions must be taken into account, as well as some alteration of the surface finish by increased roughness.

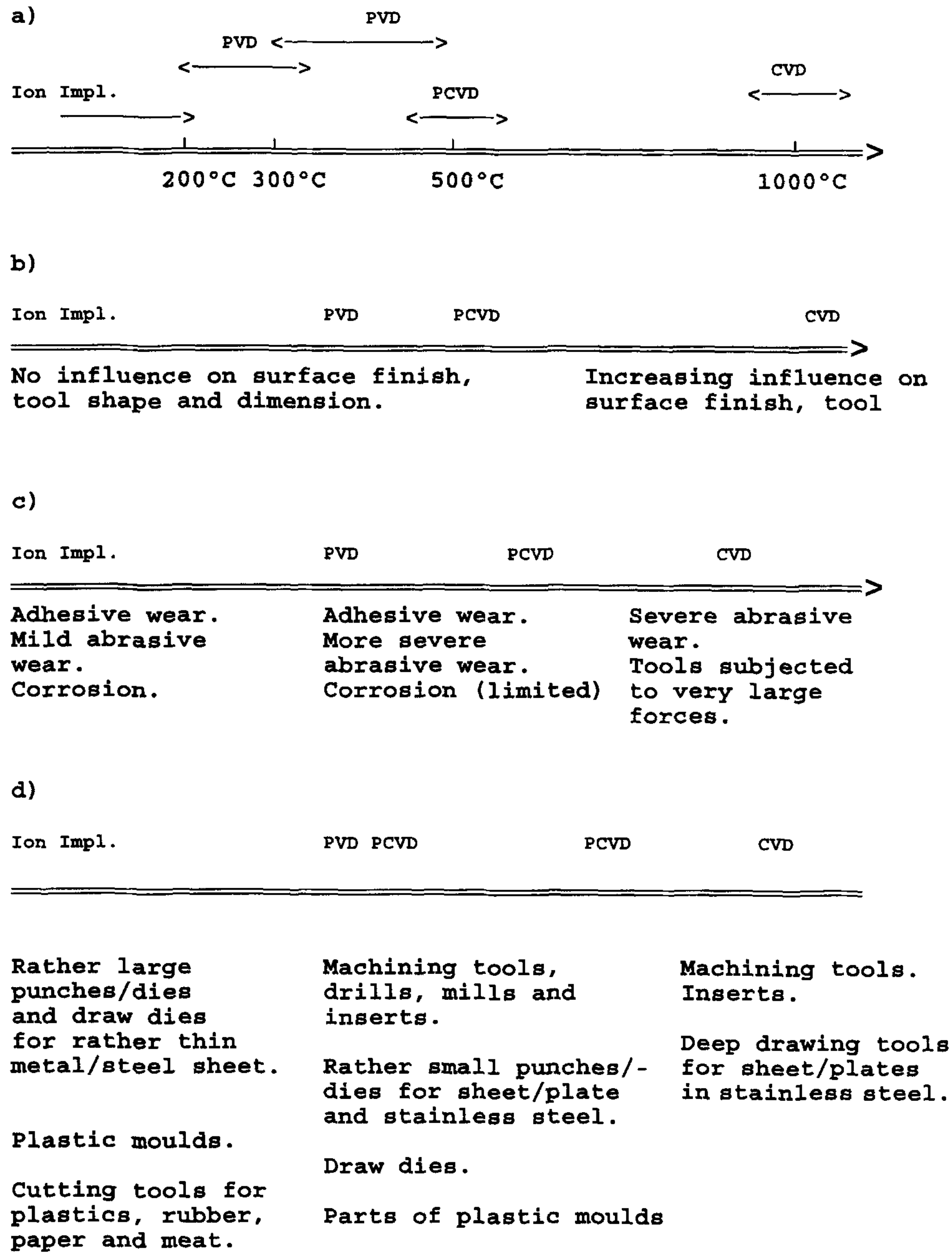

Fig. 4. Comparisons between different surface treatments: (a) process temperatures; (b) influence of surface treatment on surface finish, tool shape and dimensions; (c) capability of reducing wear; (d) typical examples of various applications in Denmark. At present PCVD is very new on the commercial 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.

PCVD is a relatively new way of producing CVD coatings at lower process temperatures [9]. The process is very similar to standard CVD, but due to the presence of a plasma in the process gases, the parts to be coated need only be heated to around 450–550 °C. The typical coatings produced are the same as for standard CVD. PCVD processes are also used to create diamond or diamond-like carbon coatings.

PVD is a common denominator for several different processes by which tools and components are coated with wear-resistant layers typically made of 2–3 μm thick TiN, TiAlN, TiCN or CrN [10–12]. The process temperature is normally about 400–500 °C. At the DTI Tribology Centre, however, a process is used [11] in which the process temperature is usually kept at about 300–350 °C, but in some cases as low as about 200 °C. 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 with CVD. Normally, the surface finish is unaltered by PVD, but for highly polished surfaces a minor increase in microroughness may be observed, depending on the PVD technique applied.

In Denmark, the surface treatment of machining tools, such as drills, mills and inserts, is primarily made by PVD or PCVD/CVD. In most cases, such tools are subjected to rather severe wear, and ion implantation is generally not as efficient as PVD and PCVD/CVD due to the shallow depth of the implanted layer. 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 the tools, making ion implantation relatively expensive in these cases.

A rough comparison of the different treatments is given in Fig. 4. The figure should only be used as a rough guide, and in several cases there are exceptions to the ranking and classification shown. However, in general, ion implantation is a very gentle, safe treatment especially suited for delicate tools. When dealing with more severe wear situations, however, the shallow depth of the implanted layer may be a limiting factor to the use of ion implantation. Nevertheless, in many applications, where tools are subjected to adhesive and/or mild abrasive wear, the treatment has proved to be second to none.

9. Conclusions

Ion implantation has proved to be a commercially feasible surface treatment of production tools. By utilizing the specific advantages of the technique, ion implantation has been successfully introduced as a commercial surface treatment of several tool types in Denmark. Thus ion implantation plays an important role in the commercial surface treatment of tools in Denmark, and has found a large and increasing number of application niches on the tool market. However, for other tool types, for which ion implantation is less appropriate and where PVD and PCVD/CVD coatings have their main application, the use of the technique is somewhat limited.

Much time is needed to implement an ion implantation product on the market. To some extent, this is also probably true for other surface treatment processes, but more so for ion implantation.

However, 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, build up and focus on the relevant niches for the process, and not to try and compete with other surface treatments in areas in which ion implantation is not the best choice. It is expected that the most successful commercialization of ion implantation will take place at establishments also offering other surface treatments.

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