Surface and Coatings Technology 158–159 (2002) 42–47
SURFACE & COATINGS TECHNOLOGY
www.elsevier.com/locate/surfcoat

Ion implantation—the job coater's supplement to coating techniques

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Abstract

Since the beginning of the 1990s, industrial application of ion implantation has increased considerably at the Tribology Centre. The Centre has focused on ion implantation techniques using steered and focused mass separated ion beams. This method has enabled the Selected Area Ion Implantation (SAII) approach, by which it has been possible to establish ion implantation as an important supplement to commercial coating techniques. In particular, industries working with plastics and thin metal/steel sheets use ion implanted tools. Injection moulds, punches, dies and drawing tools are frequently ion implanted with the result that tool life is enhanced by a factor of 3–10 and in some cases even more. For such applications ion implantation has found an important niche where it outperforms coating techniques also with respect to price. Examples of tools improved by ion implantation are given, and ion implantation is discussed in relation to the coating technologies of PVD and PCVD.

Keywords: Ion implantation; Coating; Tools; Applications; Commercialisation

1. Introduction

It has been recognised for several years that many different tribological phenomena like abrasive wear, adhesive wear, corrosion, friction, galling or sticking significantly reduce functionality and life time of many vital tools and components. Thus, much effort has been put into solving such tribological problems and it has become more and more obvious that many of these problems may be solved by appropriate use of vacuum-based surface treatments.

However, it is also recognised that not all of the various tribological problems can be solved by only one type of surface treatment. There is a growing awareness that surface treatments must be adapted to the specific situation, in which the physical and chemical properties of the treated surface must match the specific tribological phenomena. Moreover, different tools and components can be made from different metals and steels, they may be hardened and tempered differently, be able to withstand different temperatures and exhibit very different geometries. Consequently, the surface treatment process itself must also be adapted to the types of workpieces to be treated.

Thus, many different vacuum-based surface treatments have emerged and many of these are used for tribological purposes. Among the best known are ion implantation, PVD (physical vapour deposition), PCVD (plasma chemical vapour deposition) and plasma nitriding.

These techniques have very different characteristics, and they are capable of synthesising many different surface treatments with specific tribological properties. They also have different process temperatures and influence the workpiece/surface geometry differently. And they differ quite a lot with respect to handling workpieces of various geometries.

This is of significant importance to many job coating centres, and in order to be on the leading edge in the field, the Tribological Centre has found it necessary to establish a large portfolio of different vacuum based surface treatments made by ion implantation, PVD, PCVD and plasma nitriding.

Thus, by appropriate use of tailored surface treatments made by these techniques (or combinations of these), the Tribology Centre has found optimum solutions to many of the different and most pronounced tribological problems seen on tools and wear parts. A large number

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PII: S0257-8972(02)00208-6

of these problems are solved by using ion implantation, and ion implantation has become one of the Centre's most important commercial surface treatments.

2. Selected area ion implantation

It is often claimed that ion implantation is a very difficult process to commercialise, especially when used for tribological purposes. It is said that the process is expensive mainly due to very complicated and high cost equipment and very long process times. In order to overcome some of these problems much effort has gone into reducing the process times by enhancing the efficiency of the ion implanters. Increasing the ion current and lowering the complexity of the equipment have been the main solutions.

Thus, at several places much attention has been put into establishing new ion implantation processes with very high ion currents (10–100 mA or even more). Very efficient ion sources and new concepts based on the Plasma Immersion Ion Implantation (PIII) principles have appeared, offering new and interesting approaches to how to facilitate commercialisation of the process. In these approaches the main idea is either to direct a static broad and unidirectional very high-current ion beam towards the whole batch of workpieces or to electrically bias and immerse the workpieces directly into the intense plasma [1–5].

Such techniques have shown many promising results. However, in general it may still be concluded that commercialisation of ion implantation technologies has been harder than expected and on a world wide basis ion implantation is still far less commercialised in the field of tribology than for instance PVD.

The Tribology Centre has sought other ways in order to establish a commercial ion implantation facility. Instead of using very high ion currents, the Centre uses a modified version of the Danfysik 1090 ion implanter which has a mass separated ion beam and an advanced ion beam focussing and steering technique [6,7].

On this facility only medium to high ion currents in the order of 1–10 mA are used, and the accurate ion beam steering technique utilises the ion beam to an extremely high degree. Instead of subjecting the whole surface of workpieces to the ion beam, the advanced ion beam manipulation techniques makes it possible to implant only the relevant areas of the workpieces [8–10].

By using this Selected Area Ion Implantation (SAII) method it is possible in many cases to reduce the implanted area by orders of magnitude when compared to the more traditional 'broad beam' or the 'immersion' techniques, and the SAII technique is therefore especially well-suited for tools and components, where the relevant surfaces to be treated are relatively small when compared to the entire surface of the workpieces.

For such tools and components, it has become evident that very high ion currents are not necessary to get low implantation times. Thus, by using SAII, implantation time can easily be reduced by an order of magnitude when compared to the 'broad beam' technique. By this, fast and commercially feasible processes can be established by using only medium to high ion beam currents in the order of 1–10 mA. It should also be noted that using only 1–10 mA of ion beam current instead of for instance 10–100 mA to a great extent limits the total ion beam power on the workpieces. Thus, most of the SAII processes have a moderate ion beam power of only 100–500 W. This makes cooling of the workpieces simple, and it makes SAII a low temperature process operating at temperatures typically below 200 °C [8].

In this context, ion implantation has found a number of important niche areas on the commercial market, and the strategy on the market has been to identify, develop and industrially implement a number of different ion implantation treatments for some specific applications in the tooling industry.

Below are given examples of the development of a number of ion implantation processes with specific and unique tribological properties. Commercial application of these processes is widespread, particularly in the tool industry, and they feature among the most essential and widely used products available to the Tribology Centre's customers. The examples will be related to actual practical problems in industry, which have been solved by these treatments.

3. Examples of ion implantation processes with specific tribological properties

3.1. Corrosion protection of injection mould vents

Injection mould vents are often exposed to corrosive attack from aggressive gases from plastics. In spite of careful choices of tool design and tool steel, local corrosive attack at the vents tend to occur, resulting in decomposition of the steel and destruction of the expensive tool.

Due to the very low process temperature and the fact that no coating is applied, ion implantation is extremely well suited for delicate injection moulding tools. For this type of tools surface treatments based on ion implantation have been developed, of which ion implantation with chromium is among the most used. Local chromium ion implantation at the vents of the tools can re-alloy the utmost steel surface with very high concentrations of chromium.

Due to the formation of chromium oxides, the steel surface is passivated and its ability to withstand corrosion in these areas will be improved. If chromium ion implantations are performed in the ordinary way in a high vacuum, the system will exhibit a relatively high

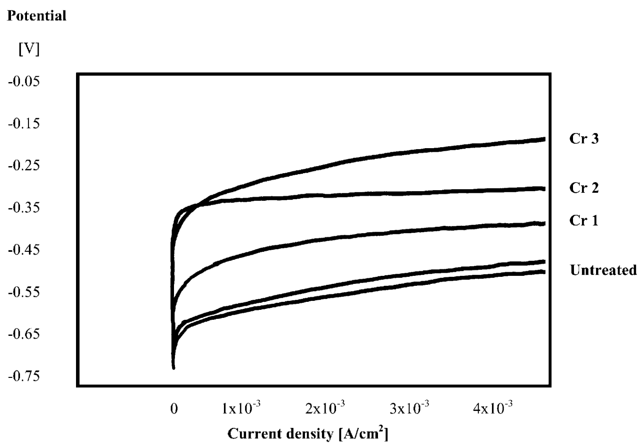

Fig. 1. Pitting potential measurements of chromium implanted Rigor steel.

sputtering coefficient. This means that the obtainable retained chromium dose in the steel is relatively limited.

However, the chromium ion implantation method has been improved, and by performing high dose chromium ion implantation in a thin O_2 atmosphere, the sputtering coefficient will be markedly reduced, enabling the retainment of a considerable part of the implanted chromium in the steel surface. By this method, chromium concentrations of up to 40 at.% can be obtained.

Part of the characterisation of the chromium ion implanted surfaces is corrosion testing of chromium ion implanted test samples using pitting potential measurements which are carried out according to the standard of ASTM G 61-86.

As an example, Fig. 1 shows the current density, as a function of the potential of untreated and chromium implanted steel samples, respectively, (hardened Rigor steel, W.no. 1.2363). A relatively high level of potential indicates a relatively high (pitting) corrosion resistance. Designations Cr 1, Cr 2 and Cr 3 indicate chromium implanted samples with progressive amounts of chromium in the surface. The designation untreated includes also an additional control measurement made on another untreated test sample. As a result of chromium implantation, pitting corrosion resistance of the Rigor steel is seen to be clearly improved, with best results obtained at the highest doses of chromium. Moreover, the results have been compared with microscopy inspection of the corroded samples, typically showing that the extent of corrosion mirrored the results of the potential measurements closely.

In addition to the above, industrial users have agreed to perform field tests of chromium implantation of selected production tools. The results of the field tests were the same as for the laboratory tests, showing dramatically reduced corrosion of the moulds due to chromium ion implantation. Today the process has been tested thoroughly and is used extensively by the customers of the Tribology Centre. The process is often able to prolong the life of mould parts exposed to corrosion by 3–10 fold, giving our customers substantial financial gain.

Fig. 2 shows a form plate of an injection mould. Severe corrosive attack was seen on the hardened steel form plate, localised to most of the hole edges. Chromium ion implantation of the attacked areas eliminated corrosion and improved tool life dramatically. Since ion implantation by the SAII method is performed locally in the relatively small area near the hole edges, it is possible to carry out the implantation in a fairly short time. This makes the price of implantation only a fraction of the actual price of the tool. The example is characteristic of the Tribology Centre's large output of chromium ion implantation of injection moulds.

3.2. Reduction of adhesive wear in sheet forming

Primarily, bending, drawing and punching tools for very thin metal sheet and tin plate are subjected to adhesive wear, which causes micro-welding of the sheet metal to the tool surface. This will reduce the functionality of the tool, and in very serious cases it will lead to subsequent damage of the tool surface by galling. As is well known from nitriding processes, introduction of major concentrations of nitrogen into the steel surface will result in a higher degree of passivation of the surface with respect to micro-welding against other metals, reducing or eliminating micro-welding and galling, i.e. adhesive wear.

For very thin sheet, e.g. tin cans, very precise and delicate bending, drawing and punching tools are used. Many of these tools can not withstand heating, surface expansion, alteration of the surface finish or deposition of a surface layer, which inhibits the use of coating and

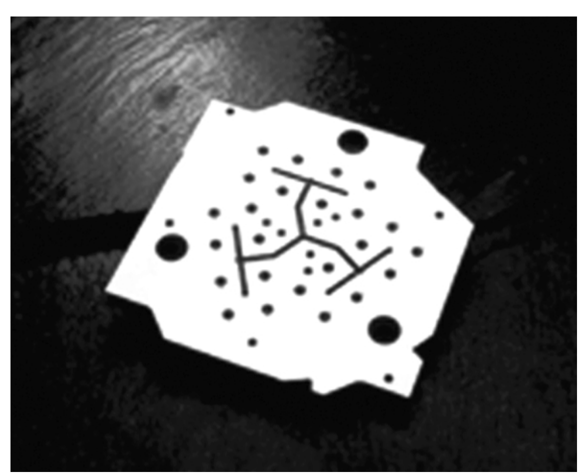

Fig. 2. Corrosion of injection mould vents can be remedied by chromium implantation.

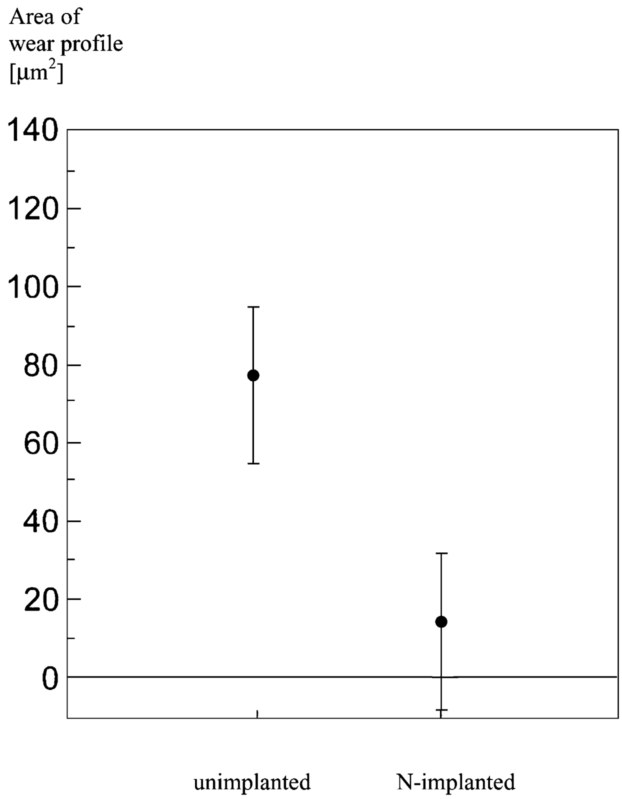

Fig. 3. Pin-on-disc wear test carried out on nitrogen implanted Sverker 21 steel.

nitriding techniques and makes ion implantation of nitrogen a highly recommendable choice.

As a result of this, various methods of nitrogen implantation of bending, drawing and punching tools have been developed. Characterisation of these methods has been carried out in part by means of pin-on-disc (POD) wear test methods of ion implanted steel samples.

For the particular purpose of evaluating the tendency of a surface to micro-weld against other metals, we use one method, among others, in which an aluminium pin under a constant load runs dry, i.e. unlubricated, against a rotating steel disc. Aluminium is known to be extremely willing to micro-weld against steel, for which reason this material is used particularly for testing adhesive wear. The tests are carried out in very well controlled conditions with respect to load, test atmosphere, relative humidity, rotatory speed, sliding speed, sliding distance, alignment, mechanical stability, etc.

During the POD tests, friction between pin and test sample can be followed and after testing, wear of the pin and test sample can be measured. Wear of the test sample itself is measured by profilometry, enabling the determination of worn off sample material or built-up material in case of adhesive wear.

POD testing is carried out with parameters with a close resemblance to the loads applied to the actual tools. It must, however, be emphasised that in many cases an exact picture of the wear situation under a given tool situation can not be given by POD tests. Therefore, POD tests are mainly used for comparative tests, e.g. of two different surface treatments.

Fig. 3 shows the result of POD tests of nitrogen ion implanted and hardened Sverker 21 (W.no. 1.2379) steel samples. In the figure, the average value of the amount of built-up aluminium from the pin can be seen. The figure shows a marked reduction of adhesive wear, reducing the build-up of aluminium on the steel. This observation is corroborated by a very large number of industrial applications to the benefit of manufacturers of sheet metal containers in particular and resulting in typical life improvement by 3–5 fold or more, see Fig. 4.

4. Ion implantation compared to PVD, PCVD, CVD and plasma nitriding

As illustrated by the examples above, ion implantation at the Tribology Centre has found its niches in the tooling industry. Several other applications have been established, and today many companies improve their production tools by applying ion implantation on a regular basis [6–8].

In general, the most successful markets have been obtained where using the specific advantages of the SAII technique has been possible, e.g. in the following tool areas:

- Tools tempered at low temperatures (e.g. <200 °C)
- Precision tools whose shape is likely to be altered by heating
- Highly polished tools
- Tools where, in spite of the enhanced life, refurbishment should still be easy and possible
- Very expensive tools, since the risk of negative effects is very small
- Rather large tools on which the wear area is relatively small

Fig. 4. Adhesive wear of precision punching tools for manufacturing sheet metal containers is reduced by nitrogen ion implantation.

Table 1
Comparison between ion implantation, coating technologies and plasma nitriding techniques; typical examples are also shown of various applications of different surface treatments

	Surface treatment				
	Ion implantation	PVD	Plasma nitriding techniques	PCVD	CVD
Process temperature	<200 °C	180–450 °C	480–580 °C	500–520 °C	Approximately 1000 °C
Influence on surface finish, tool shape and dimensions	No influence	No or very limited influence. Adds a 2–5-μm-thick coating to the surface.	Some influence on surface finish Some influence on tool shape and dimensions depending on steel type Adds several microns to the surface depending on the process	No or very limited influence on surface finish. Some influence on tool shape and dimensions depending on steel type. Adds a 2 –5 μm thick coating to the surface.	Significant influence. Re-hardening after CVD is needed. Adds a 3–10 μm thick coating to the surface
Has optimum properties against	Adhesive and mild abrasive wear and moderate corrosive wear	Adhesive wear to some extent. More severe abrasive wear and mild Corrosion.	Adhesive wear Mild abrasive Wear. Mild corrosion.	Adhesive wear. More severe abrasive wear.	Very severe wear and very large surface loads
Typical application areas in the tooling industry	Rather large punches/dies for thin sheet. Very delicate precision tools Injection moulds Cutting tools for rubber paper and meat.	Machining tools, drills, mills and inserts etc. Rather small punches for sheet/plate. Drawing dies. Parts for injection moulding	Standard wear parts and components. Rather simple parts for forming tools For duplex treatment of tools, where plasma nitriding is used to enhance the steel hardness before PVD/PCVD coating	Machining tools, drills, mills and inserts etc. Rather small punches for sheet/plate. Drawing dies. Non-'line-of-sight' geometries to some extent	Machining tools, deep drawing tools for sheet/plates in stainless steel. Non-'line-of-sight' geometries

It should also be noted that at the Centre, surface treatment of machining tools like drills, mills and inserts is primarily made by the coating technologies of PVD or PCVD/CVD. Such tools are mainly subjected to rather severe wear, and due to the shallow depth of the implanted layer ion implantation may not be the most efficient treatment on machining tools when compared to PVD and PCVD/CVD.

Although there are exceptions, most machining tools have relatively small dimensions, making the SAII technique difficult to utilise. Thus, it has been difficult to fix the prices of ion implantation on machining tools at a level where they can compete with PVD, PCVD and CVD prices.

Table 1 summarises some of the properties of ion implantation in comparison with other surface treatments. This summary should be used as a rough guide only, and in several cases there are exceptions to the classifications shown in the table.

In general terms, ion implantation is considered to be a gentle and very safe surface treatment especially suited for delicate precision tools subjected to local corrosion, adhesive wear or mild abrasive wear. 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.

5. Conclusion

Ion implantation has proved able to improve the tribological performance of production tools. The technique has several specific advantages when compared to other surface treatment techniques such as PVD, PCVD, CVD and plasma nitriding. By utilising the specific advantages of the SAII technique, ion implantation has been successfully introduced as a commercial surface treatment for several tool types. For such applications the ion implantation processes have shown superior properties when compared to coating technologies, and for these applications the treatment has proved to be second to none, also with respect to price [6–8].

However, for other tool types and components where ion implantation is less appropriate, and where PVD, PCVD, CVD and plasma nitriding have their main application areas, the application of the technique is somewhat limited.

Thus, ion implantation plays an important role in commercial surface treatment at the Tribology Centre and has found a large and increasing number of niche applications on the tool market. It is therefore believed that many other job-coating centres could benefit from using ion implantation, using the process as an important supplement to their coating technologies.

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