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Industrial implementation of ion implantation on tools and wear parts based on a strategic approach

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Abstract

Ion implantation is gaining solid ground in industry in some areas while in many other areas it is still looked at as a technically interesting, but very exotic and expensive, process.

We will present points of view on how to improve the industrial implementation of the process. This involves aspects on how to make the industry see the process as just another industrial process with unique properties and acceptable prices. It includes the need to look for niche areas where ion implantation technically and economically outperforms other processes such as physical and chemical vapour deposition (PVD and CVD). It is very important to be aware of the coupling between the relevant niche areas and the available ion implanters. For owners of an accelerator with a focused ion beam that can be scanned in a controlled manner and with an advanced sample manipulator it is very obvious to go for special tools where the selected area ion implantation (SAII) technique is used to its full potential in order to give good results at a low price. This can typically be tools (relatively large) with a small critical area to be treated. Such tools will normally be rather expensive to treat with physical vapour deposition (PVD) techniques and quite cheap to treat with the SAII technique. If a high current broad beam accelerator, a plasma source ion implementation (PSII) or a plasma immersion ion implementation (PIII) machine is available, most likely another type of tool or wear part should be aimed for.

We will give examples from industry where ion implantation is accepted as a standard process and where the special possibilities of the SAII technique have been utilized to their full potential. © 1998 Elsevier Science S.A.

Keywords: Industrial application; Niche markets; Process induced heating; Selected area ion implantation

1. Introduction

For many years it has been stated that the industrial use of ion implanted tools and components was prevented by the high cost of the treatment. Thus, much effort has been put into developing ion implanters capable of producing very high ion beam currents. New high current ion implanters have been developed with very efficient ion sources and new techniques such as plasma source ion implantation (PSII) [1] and plasma immersion ion implantation (PIII) [2]. The main concept is either to direct a static, broad and unidirectional, high current ion beam towards the whole batch of workpieces or to electrically bias and immerse the workpieces directly into the plasma.

In recent years, however, a new approach has emerged in addition to these techniques. Instead of subjecting the whole workpiece to the ion beam, accurate ion beam steering techniques have made it possible to perform ion implantation only on the relevant areas of the workpiece [3,4]. This selected area ion implantation (SAII) technique can be applied on many types of workpieces, reducing the implanted area by orders of magnitude when compared with a broad beam approach. Thus, for the right kind of tools and components, very high ion beam currents are not needed and the process time can be reduced by orders of magnitude.

However, it should be noted that, in any case, market acceptance of these techniques is only obtained when using a strategic approach [5]. New and improved ion implantation techniques have been developed, but we must take into consideration the extensive development of related coating processes or surface treatments like PVD, chemical vapour deposition (CVD), plasma-CVD (PCVD) and plasma nitriding. These treatments have developed rapidly and have gained very large market acceptance in different areas.

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It is therefore very important to find the proper niche markets for the new generation of ion implantation techniques. By selecting the right niches for a strategic market approach for the SAII technique, this technique has now been accepted as a regular surface treatment of tools in addition to PVD, CVD, PCVD and plasma nitriding for tribological purposes.

2. Important points to consider when approaching the market

2.1. Machining tools are rarely ion implanted

PVD, PCVD and CVD coating of tools has now been established in the market for many years. Such processes are normally run at temperatures of 300 °C and above, but high quality low temperature PVD (180–200 °C) coating has, in recent years, become available on the market, enabling PVD coating of temperature sensitive tools and components as well.

However, machining tools are still the main niche for PVD and (P)CVD coating. Today such tools are coated to a great extent. Not only the traditional golden TiN coating but also the new generation of coatings, such as TiCN, TiAlN, CrN and multilayers, are now widely used on the world market. Many of today's coaters are capable of producing high quality coatings at very low prices on standard machining tools which can withstand coating temperatures of up to 520–560 °C or even more. In addition, machining tools are often rather small, and most PVD and (P)CVD techniques are excellently fitted to process batches comprising hundreds or thousands of machining tools. Coating process times for such large batches are often only a few hours, and coated machining tools are therefore introduced on the market at very low prices.

At the DTI Tribology Centre, ion implantation has not been considered feasible for most machining tools. The ion implanted layer is very thin, giving little protection against the severe wear to which most of such tools are subjected. Coatings, on the other hand, have proved to provide very efficient wear protection, and even if ion implantation could be performed at prices lower than those of PVD/(P)CVD, only very few types of machining tools would benefit from it.

2.2. Potential niche area for ion implantation

In order to find the potential niches in which ion implantation works particularly well, it may be a good idea to look at some of the advantages which are generally stated for ion implantation:

- it can be made at low temperatures (<200 °C);
- the surface finish of the workpiece is totally unaltered;
- ion implantation introduces no change in shape and dimensions if made at low temperatures;
- there is no coating applied and no risk of surface delamination.

Thus, delicate temperature-sensitive and precision forming tools and components should be well suited for the process. In addition, such workpieces are often subjected to mild abrasive and adhesive wear or mild corrosion, and ion implantation has generally shown superior properties against such wear modes when compared with coatings [5,6].

3. Ion beam induced heating is of main importance

However, in order to obtain a market in this area the cost of the treatment must be kept at a relatively low level, i.e. process times must be short. This can be obtained by using very high ion beam currents. However, it may be hard to avoid severe process induced heating of the workpiece during high current implantation. For instance, if a batch of tools is to be implanted by using a broad stationary beam with a diameter of $\varnothing \approx 45$ cm, then the beam area would be about 1590 cm^2. Owing to the complex geometry of most tools or components, rotation of the target/workpiece is needed where the axis is held at 45 ° from the beam direction. Thus, the net area to be implanted is $1590\ \text{cm}^2 \times \pi = 4995\ \text{cm}^2$. The process time for such batches would be in the order of 50–150 h for 1 mA of beam current. In order to obtain a process time of a few hours, similar to many PVD processes, beam currents in the order of more than 25 mA are needed.

Implantations for tribological purposes are normally made at ion energies in the order of 100 keV. Thus, if for instance a 100 keV and 25 mA ion beam is used, the total beam power would be 2.5 kW, and the power density would be 1.6 W/cm^2 perpendicular to the beam. When using a broad beam, a very large part of the workpiece surface is subjected to the beam power, and the total amount of power impact can be very high. Even for workpieces perfectly mounted on a water-cooled holder and with an ideal thermal contact to the holder, process-induced heating of more than 300 °C is easily obtained [7]. For real workpiece mounting, the thermal contact is often far from ideal and heating can become even more severe. The question is what to do. There seems to be four options:

(1) The heating could be accepted if this would not compromise the properties of the tool and the surface treatment itself.
(2) The batch area could be expanded to, for instance, $\varnothing$ 90 cm.
(3) The beam current could be lowered. This, however, would make the implantation expensive.
(4) The total power impact on the workpieces could be

lowered by reducing the surface area of the workpiece subjected to the ion beam.

Option 1 would imply that ion implantation no longer is considered a cold process. By this, ion implantation would not be used on the tools and components where it is known to have superior properties. It would be introduced on a market where PVD, (P)CVD and plasma nitriding are known to have remarkable results and low market prices.

Option 2 would imply for instance that a 2.5 kW ion beam (i.e. a 25 mA and 100 keV ion beam) instead of having a power density of 1.6 W/cm^2 (as for the ∅ 45 cm batch) would have a power density of 0.4 W/cm^2. This would lower the total power input on each workpiece by four times. However, most of the area of the workpieces is still subjected to the beam and the total power impact on each workpiece is still rather large [7]. However, for some batch set-ups it may be possible to establish a low temperature process. The total process time would be four times the process time for the "high temperature" ∅ 45 cm batch, however, the ∅ 90 cm batch could contain four times the number of workpieces. Thus, the cost per workpiece could be quite similar for the two batch modes. However, this only applies if it is possible to utilize the large batch capacity by filling up the chamber with four times the number of workpieces compared with the small batch mode. Very large batch modes would therefore only be feasible economically if the process chamber is filled to its capacity in most cases. At DTI Tribology Centre we have experienced that, for all advanced surface treatments such as PVD, (P)CVD and ion implantation, it has been economically sounder to run with medium batch sizes about max. ∅ 50 cm. By this, we have been able to efficiently adapt the surface treatment production to the size and character of the various orders we get from customers. This would not have been possible if, in each case, we were obliged to fill up batches of sizes in the order of ∅ 1 m or more.

Option 3 would imply an expensive treatment when compared with coating and nitriding. Market acceptance could then only be gained if ion implantation results in tribological properties which are vastly better than obtainable by coatings or nitriding. To the best of our knowledge, this is not the case.

Option 4 would imply that ion implantation could be made at low temperatures, at low process times, and with flexible batch sizes, enabling a low-cost treatment. However, the ion implantation technique must be adapted to this. By using a well-controlled focused and steered ion beam, implantation can be made in selected areas only. However, in order to utilize this, only workpieces having a relatively small critical area compared with the total workpiece area are suited for this approach. A large amount of high-precision tools actually fulfil this requirement. And at DTI Tribology Centre a large market mainly based on this niche has been established.

4. Examples of SAII of tools

4.1. Rather large punches for thin sheet forming

DTI Tribology Centre ion implant a large number of rather large high-precision steel punches for thin sheet formation on a regular basis. Such punches are subjected to mild abrasive and adhesive wear. Such tools normally produce many hundred thousand items when unimplanted, however, by nitrogen ion implantation several million items can be produced. For at typical ring-shaped punch (size ∅ 20 cm) the critical area at the cutting edge that must be optionally and homogeneously implanted is about 63 cm^2. Such a tool is implanted by directing a focused beam with a beam diameter of about ∅ 1 cm, horizontally fixed and scanned 1.8 cm [$= \cos(45°) \times 1 + 1$ cm] in the vertical direction towards the centre of the critical area on the rotating tool and with the rotational axis held at 45° from vertical.

Several such tools can be mounted in one batch where a PC programme controls the ion beam, enabling it to shift frequently from tool to tool [3,4]. 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 3×88 cm^2 (area of "wasted beam"), in total 453 cm^2. With a beam current of 4 mA N^+, the typical process time would be about 1.5–3 h for the whole batch, and each tool is only subjected to about 100 W of beam power. Cooling the tools through the watercooled tool manipulator is therefore easy, even with simple fixtures. If a similar batch has to be made by using a broad beam approach and with a similar low power impact, the process time would be more than 10 times longer. The price of PVD coating similar tools would be at least two times the price of the SAII, and in these cases nitrogen implantation has shown superior tribological properties when compared to coatings.

4.2. Injection moulds subjected to local corrosion

Many steel moulds used for injection moulding are subjected to local corrosion near the vent caused by the emission of aggressive gases from the plastics during the process. By chromium ion implantation corrosion can be prevented and tool life can be enhanced by three to five times. Such moulds may typically have dimensions in the order of $10 \times 30 \times 30$ cm. In the present case, 12 vents are placed in a regular pattern on the 30×30 cm surface of the tool and each critical area of the vents is about 4 cm^2. Thus, the area to be optimally and homogeneously implanted is about 12×4 $cm^2 = 48$ cm^2. Such a tool is implanted by directing a focused beam with a beam diameter of about ∅ 1 cm perpendicular to the surface and applying a horizontal and vertical beam scanning $[(2+1)\times(2+1)\,cm^2=9\,cm^2]$ over the critical area of each vent, with the beam position shifting automatically between the 12 vents. The implanted area is 108 cm^2 in total including the area of "wasted beam". Such a tool can be treated in about 1 h and without the risk of unintentional heating. If the whole $30\times30\,cm^2=900\,cm^2$ area had to be implanted by using a broad beam approach, the process time would instead have been almost 9 times longer when using the same ion beam current.

5. Typical niches for SAII

For several years, DTI Tribology Centre has offered commercial ion implantation based on the SAII technique [8]. Ion implantation has been offered in addition to other surface treatments like PVD, PCVD and plasma nitriding, and the use of the SAII techniques has made it possible to create rather large markets on tool types where SAII is second to none both pricewise and technically. Typical tool types are:

- rather large, delicate, high-precision punches and forming tools for thin sheet forming;
- injection moulds;
- very sharp knives for paper, cardboard, plastics and meat.

Today, thousands of such tools and tool parts are ion implanted at DTI Tribology Centre each year, and ion implantation has become a large and integral part of the regular production at the Centre.

6. Conclusions

High current broad beam ion implantation, PSII and PIII techniques have been developed intensively in recent years, and interesting and promising results have been obtained. It is important, however, to consider which kind of application niches these techniques will have in the future. If workpiece heating during the processes is inevitable, these techniques will, to a great extent, be in direct competition with well established PVD, (P)CVD and plasma nitriding techniques. These factors should be taken into account when finding the right niche applications for the high current ion implantation techniques.

The SAII technique offers an alternative approach. It has been shown that by using the SAII a productivity gain of about 10 times and a corresponding lower cost of ion implantation can be obtained. However, this is only valid for those types of tools and components which are suited for this process. By careful selection of the niche market for application of the SAII technique, a sound and regular market for commercial ion implantation has been established. Furthermore, the SAII is something that, to the customer, strongly and, in many cases, very positively distinguishes ion implantation from other processes like PVD or (P)CVD where it can be difficult and certainly expensive to make selected area treatment.

If high current broad beam ion implantation, PSII or PIII techniques are 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.

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