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The improvement of wear resistance by ion implantation*

by R. HUTCHINGS†

SYNOPSIS

The paper reviews current understanding of the effect of ion implantation on the wear process, and the state-of-the-art of ion implantation as a commercially viable treatment to impart wear resistance.

Ion implantation involves the firing of high-energy ions into the surface of a material, which modifies the surface properties and so causes a transition in the dominant wear mode. The process is best suited to specialized engineering applications involving critical dimensional tolerances or surface finishes, but has gained little industrial acceptance because of its poor reproducibility and the lack of a suitable method of inspection.

SAMEVATTING

Die referaat gee 'n oorsig oor die huidige begrip van die uitwerking van iooninplanting op die slytproses en die kundigheidsvlak van iooninplanting as 'n kommersieel lewensvatbare behandeling om slytbestandheid te verleen.

Iooninplanting behels die inskiet van hoë-energie-ione in die oppervlak van 'n materiaal in wat die oppervlakeienskappe wysig en só 'n verandering in die oorheersende slytwyse veroorsaak. Die proses is die geskikste vir gespesialiseerde ingenieursaanwendings waar afmetingstolerasies of oppervlakafwerkings van kritieke belang is, maar is nie juis op nywerheidsgebied aanvaar nie vanweë die swak reproduseerbaarheid daarvan en die gebrek aan 'n geskikte inspeksiemetode.

Introduction

In 1972 Hartley, Dearnaley, and Turner[1] reported that ion implantation was capable of reducing the friction coefficient of metals that were subjected to sliding contact. This observation provided the impetus for extensive research into the use of ion implantation as a technique for the modification of the wear resistance of materials. Since 1972 considerable advances have been made in the understanding of the fundamentals of ion implantation, and a number of successful engineering applications have been reported. Dearnaley[2] gives several examples of these. However, ion implantation is still far from being a technique that is generally accepted by the engineering community.

The purpose of this paper is to review both the current understanding of the effect of ion implantation on the wear process and the state-of-the-art of ion implantation as a commercially viable treatment to impart wear resistance.

The Ion-implantation Process

Ion implantation involves the firing of high-energy ions into the surface of a material. Typically, these ions have energies in the range 20 to 200 keV. Theoretically, the implanted ions produce a Gaussian distribution below the surface of the material, with a peak concentration at a depth of about 100 nm. Fig. 1 shows the experimentally determined profile for nitrogen implanted into Ti-6Al-4V. The nitrogen was implanted to a dose of 3,5 $\times 10^{21}$ ions per square metre at an energy of 90 keV, and the analysis was performed by ion back-scattering.

From Fig. 1 it can be seen clearly that implantation provides a means of introducing very high concentrations (more than 50 atomic per cent) of a foreign species into a metal surface. In addition to modifying the subsurface composition, implantation results in the introduction of considerable damage due to the displacement of atoms by collision processes. The incorporation of the implanted atoms also produces a region of residual compressive stress close to the surface. Thus, ion implantation is a very versatile technique for surface modification, especially as the choice of species to be implanted is limited only by the necessity to ionize that species.

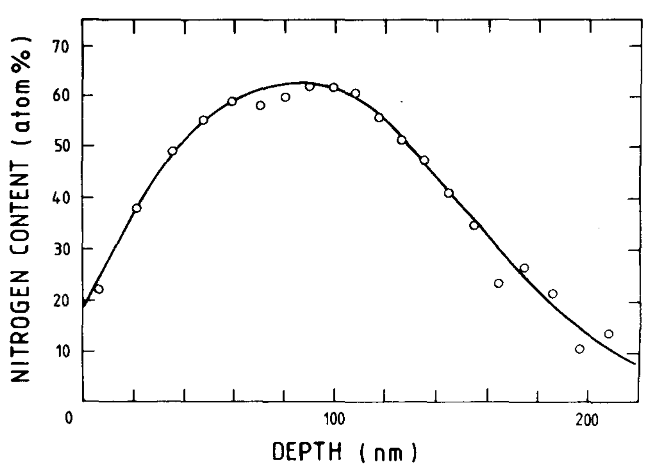

Fig. 1—Ion back-scattering results for nitrogen implanted into Ti-6Al-4V to a dose of 3,5 $\times$ 10^{21} ions per square metre at 90 keV. The analysis was performed by use of the N^{14} (α, α) N^{14} reaction with an incident energy of 3,4 MeV

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† Department of Materials Engineering, University of Cape Town, University Private Bag, Rondebosch, 7700 Cape Province.

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Ion-implantation Equipment

In early studies, use was made of large, general-purpose accelerators of the type found only in nuclear-physics laboratories. In the early 1970s, because the development of commercial implanters was dominated by the needs of the semiconductor industry, the early implanters were low-current systems, with magnetic separation of the ion beam to ensure high purity.

With the emergence of ion implantation as a technique for metallurgical applications, it was realized that alternative criteria were important. Generally, a higher concentration of the implanted species was needed and the areas to be treated were much larger, resulting in the necessity for higher beam currents so that components could be treated in a reasonable time. The more intense beams, in turn, led to heating problems and the need for cooling of the components. On the positive side, purity was less important and it became acceptable to dispense with beam separation.

The work of Dearnaley's group at the Atomic Energy Research Establishment at Harwell showed that nitrogen was particularly effective in improving the wear resistance of a wide range of steels. In view of this, and the relative cheapness and simplicity of a gaseous ion source, an industrial implanter based on nitrogen implantation was developed at Harwell; this was the PIMENTO (Prototype Implantation Machine for Engineering Tools). Such a system is shown schematically in Fig. 2.

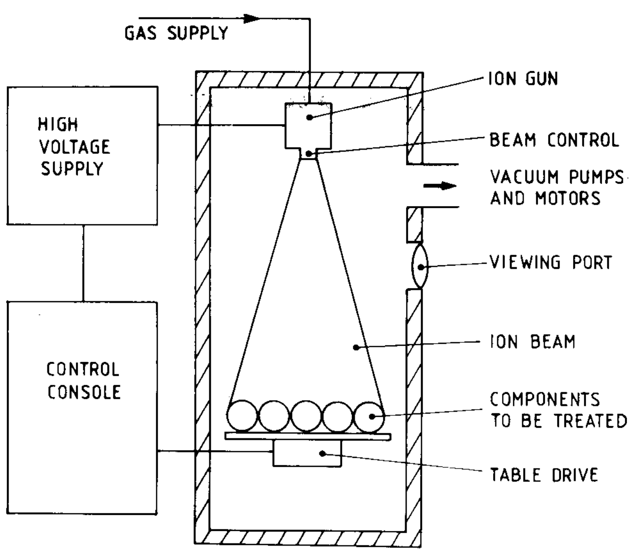

Fig. 2—Schematic representation of a metallurgical ion-implantation system

The metallurgical implanter consists basically of a vacuum chamber, ion gun, and component table. The handling of components is critical since implantation is a line-of-sight process and the components must be manipulated to expose the critical areas for the requisite time while the components are kept cool. The PIMENTO is capable of producing a beam of 5 mA spread over an area of 25 by 10 cm, indicating a maximum current density of 20 $\mu A/cm^2$. In normal use, a working current density of 5 $\mu A/cm^2$ will give a dose of 4×10^{21} ions per square metre in approximately 4 hours for a simple component while maintaining the temperature of the component below 150°C.

It should be pointed out that accurate calculation of the amount of nitrogen implanted in such a system is difficult. The ion current can be monitored, but a simple ion gun of the type used produces a mixed beam of singly charged nitrogen atoms (N^+) and singly charged nitrogen molecules (N_2^+). The ratio of N_2^+ to N^+ ions depends on the operating conditions, but is approximately 3 to 1 for the normal working conditions specified above.

Properties of Implanted Layers

In general, implantation produces chemical and microstructural changes in a thin surface layer, which influence the microscopic, and in some cases macroscopic, properties of the material. The major changes that affect the wear resistance of implanted metals, particularly nitrogen-implanted metals, are considered below.

Hardness

Hardness is probably the most important single parameter governing wear resistance. Increasing hardness generally decreases friction and the rate of wear, provided that the surface does not exhibit associated embrittlement. Nitrogen implantation has been shown[3] to increase hardness by two basic mechanisms: interstitial hardening, and nitride precipitation. The nitride may be present in the form of a fine dispersion or as a discrete nitride layer[4]. The degree to which a material can be hardened will clearly depend on the concentration of strong nitride-formers in an alloy and the degree of which the parent lattice has already been hardened. This is exemplified by the fact that pure aluminium shows a maximum increase in hardness of a factor of 4, whereas AISI–SAE 52100 bearing steel shows no increase in hardness.

Microstructure

Implantation produces a marked refinement of the grain structure of the implanted layer. The damage produced directly by inter-atomic collisions breaks up the crystal structure. In most cases, crystallinity is still maintained by relaxation processes, but the low temperatures and short diffusion distances lead to small well-dispersed precipitates that tend to stabilize the refined grain structure. These same criteria lead to the fine grain size of discrete nitride layers that may form, which helps to confer good wear resistance on the implanted materials.

In the extreme case, certain implanted species have been found to hinder the thermally activated relaxation processes, giving rise to the stabilization of amorphous implanted zones. This has been shown[5] for Ti^+ implanted into high-purity iron, and may well explain the improved wear resistance of Ti-implanted AISI–SAE 52100 steel at doses at which no hardening occurs[6]. It should be pointed out that the majority of the evidence indicates that gettered carbon plays a significant role in stabilizing the amorphous layer.

Wear Resistance

Improved wear resistance in shop-floor tests of implanted components provided the driving force for further investigation of ion implantation as a surface treatment. However, such tests were often poorly controlled and did little to elucidate the mechanisms by which ion implantation effected these improvements. Subsequently, more controllable laboratory tests have furthered our understanding, but a number of uncertainties still exist.

Early explanations for the effect of nitrogen were simply based on increased hardness. Such arguments were obviously inadequate since, in some cases, wear rates were found to be reduced by 2 or 3 orders of magnitude when the increases in surface hardness were less than 200 per cent. It has now been shown that such large improvements in wear resistance are obtained when implantation triggers a transition from the normal mode of wear to a less severe mode. A good example[7] of such a transition is shown by the sliding wear of nitrogen-implanted Ti-6Al-4V, which undergoes mild oxidative wear, instead of the severe adhesive-abrasive wear exhibited by the unimplanted material. The effect of the nitrogen is to harden the alloy and reduce the initial rate of wear, allowing a thin layer of oxide to form. The nitrogen must also stabilize the oxide (either mechanically or chemically) because the process of coarse, adhesive wear takes over immediately the implanted layer is worn away.

Early reports claimed that the implanted nitrogen moved into steels ahead of the advancing wear surface, thus conferring improved wear resistance at wear depths much greater than the original thickness of the implanted layer. This is now accepted as being the exception rather than the rule[8], and in most cases beneficial effects are lost when the average depth of wear exceeds the depth of implantation. Prolonged improvement has been conclusively established in several instances such as the work of Hale and his co-workers[9] on nitrogen-implanted AISI-SAE 4135 steel. However, in that case it was shown that no nitrogen was retained at the wear surface. Thus, the previously reported ingress of nitrogen seems to be an item of scientific curiosity rather than a generally reproducible phenomenon.

Applications

Based on an understanding of the property changes that can be brought about by ion implantation, consideration can now be given to suitable areas of application. Before any specific applications are examined in detail, it is useful to review the major points that distinguish implantation from the wide range of alternative techniques of surface treatment.

The outstanding feature of ion implantation is the shallow depth of the treated zone, which provides both the major disadvantages and advantages of the technique. On the debit side, such a thin layer is of little use in a situation involving coarse abrasive wear or erosive wear and, even if the wear process is on a finer scale, a strong substrate is necessary to support the implanted layer during asperity contact. The advantage of the shallow treatment zone is the lack of dimensional change produced during treatment. This fact, together with the low treatment temperature, means that implantation can be applied to a component that has been machined to final dimensions without risk of distortion.

The cost of implantation on an industrial scale is still uncertain. Commerical implanters have become available only fairly recently, and no detailed operating costs have yet been published. However, projected figures[10] For the operating cost of a PIMENTO type of machine, which were published in 1981, suggest a value of 1 to 2 U.S. dollars per square centimetre for nitrogen implantation. Thus, it can be seen that ion implantation will find its main applications in medium- to high-cost components with critical dimensional tolerances.

Tools

Ion implantation was found to be successful in a number of tooling applications during the early work at Harwell[2]. A prime example was the greatly improved life of feed screws from a plastic moulding rig. These screws are subjected to fine abrasive wear by the inorganic filler particles in the plastic, resulting in increased clearances and poor control of the moulding pressure.

Punch assemblies for both plastic and metal sheet have also shown improved lifetimes in shop-floor tests. Fig. 3 indicates the critical areas for the implantation of a simple punch. It should be noted that implantation of the lateral faces of the punch results in retention of the implanted edge, even after multiple re-sharpening of the punch.

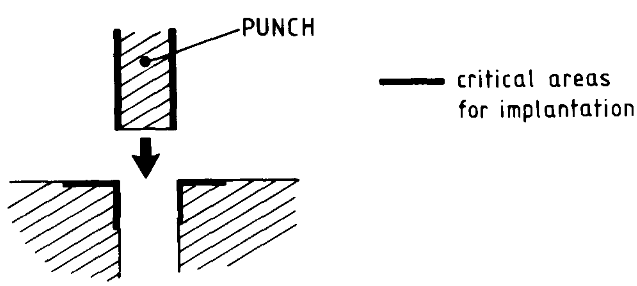

Fig. 3—Implantation scheme for a simple punch assembly

A selected list of other tooling applications, taken mainly from reference 10, is given in Table I.

Engineering Components

The Naval Research Laboratory, Washington D.C., has carried out extensive work on the application of ion implantation to bearing steels. Implantations of Ta, Ti, and Ti + C have been found to be successful in reducing the wear of AISI-SAE 52100 bearings for military aerospace applications[11]. However, such a treatment is unlikely to be economically viable in commercial applications of this steel.

In Germany, considerable effort is being put into the application of implantation to improving the wear resistance of gears[12]. Successful laboratory tests have been carried out, but no conclusive data are available from field trials. Among the potential applications currently being researched, perhaps the most likely candidate for promotion from the laboratory into service is nitrogen-implanted Ti-6Al-4V for surgical implants. For example, Williams and Buchanan[13] recently reported decreases in wear rate by a factor of at least 40 for Ti-6Al-4V wearing against ultra-high molecular weight polyethylene in simulated body fluids.

TABLE I
SUCCESSFUL TOOLING APPLICATIONS FOR ION IMPLANTATION

Application	Material	Treatment	Result
Injection moulding nozzle	Tool steel	$8 \times 10^{17} N^+/cm^2$	Much reduced wear
Forming tools	Carburized mild steel	$4 \times 10^{17} N^+/cm^2$	Greatly reduced wear
Taps for phenolic resin	M2 high-speed steel	$8 \times 10^{17} N^+/cm^2$	Life increased up to 12 times
Thread-cutting dies	M2 high-speed steel	$8 \times 10^{17} N^+/cm^2$	Life increased 5 times
Punches for acetate sheet	Cr-plated steel	$4 \times 10^{17} N^+/cm^2$	Improved product
Paper slitters	1,6% Cr 1% C steel	$8 \times 10^{17} N^+/cm^2$	Cutting life increased 2 times
Slitters for synthetic rubber	Co-cemented WC	$8 \times 10^{17} N^+/cm^2$	Life increased 12 times
Dies for copper rod	Co-cemented WC	$5 \times 10^{17} C^+/cm^2$	Throughput increased 5 times
Dies for steel wire	Co-cemented WC	$3 \times 10^{17} C^+/cm^2$	Life increased 3 times
Swaging dies for steel	Co-cemented WC	$8 \times 10^{17} N^+/cm^2$	Life increased 2 times

Industrial Status

At the present time the commercial viability of ion implantation is still questionable. The availability of implantation facilities has increased dramatically over the past three years, but the technique is far from being accepted by the engineering community.

As stated previously, implantation facilities were initially available only in large research establishments. This in itself provided a barrier to industrial acceptability. Although this situation is still true in the local context, considerable changes have occurred in Europe and the U.S.A. In England, Hawker Siddeley Dynamics produce a commercial version of the PIMENTO, and in the U.S.A. Zymet make a dedicated metallurgical implanter. In addition, a number of centres offering a routine implantation service have been established, e.g. Spire in the U.S.A., Tech-Ni-Plant in England, and AGIT (Arbeitsgemeinschaft für Ionstrahltechnik) in West Germany. However, even with its improved availability in these countries, ion implantation is still not gaining industrial acceptance.

The first major barrier to acceptance is the lack of reproducibility in the results obtained from individual implanters. This paper has described some of the successful tests on implanted materials reported in the literature. Unfortunately, nobody publishes results of their failures; yet informal discussion at implantation symposia reveals probably more failures than successes, even when people have carefully followed an accepted 'recipe' for a particular material. Contradictory results of this nature lead to a lack of confidence in the technique, and thus slow down the process of acceptance. This is true for any emerging technology, but in the case of ion implantation it is compounded by a second barrier: the lack of a suitable inspection procedure.

Quality assurance is now a prime consideration in nearly all engineering companies. This is particularly true for critical components in a high-technology industry, i.e. precisely the type of component to which ion implantation is likely to be applied. The only non-destructive method available to ensure that implantation has been executed successfully is ion back-scattering. This technique normally requires a particle accelerator capable of producing a beam energy in the MeV range. Thus, ion implantation is badly in need of a routine inspection method, and it is difficult to see it gaining any appreciable degree of widespread acceptance until such a technique is available.

Conclusions

(1) Ion implantation is capable of improving the wear resistance of a wide range of alloys, nitrogen being the most versatile implanted species.

(2) The effect of ion implantation upon wear resistance can be understood in terms of the directly modified properties triggering a transition in the dominant wear mode.

(3) Ion implantation has been applied successfully to improve the wear resistance of a wide range of tools.

(4) Ion implantation is best suited to specialized engineering applications involving critical dimensional tolerances or surface finishes.

(5) Despite the increased availability of commercial implanters, ion implantation is still failing to gain industrial acceptance owing to poor reproducibility and the lack of a suitable method of inspection.

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