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Section 5. Plasma deposition and applications
Invited Paper

Combined treatments – a way to improve surface performances

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The paper is trying to create a brief overview for the field of surface engineering with particular focus on combined treatments. The concepts of duplex treatments between plasma nitriding and PVD/PACVD coating, PVD coating and ion implantation and laser alloying/dispersing and plasma nitriding are analysed. Structure modification, including production of nano-structured coatings is particularly investigated. Some of the new layers produced by these combined treatments have been already tested under industrial conditions. The results of these tests indicated, for particular applications, an increase of the lifetime of the treated components of up to 70 times in comparison with the same components without surface treatment. Details about these experiments are also presented in the paper.

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1. Introduction

Surface engineering covers the field of research and technical activity concerning design, manufacture, investigation and utilization of surface layers. It comprises techniques involving surface modification of the components with the aim to improve the performances in terms of mechanical (hardness, wear, fatigue and coefficient of friction), chemical (corrosion), thermal (resistance at elevated temperature), electrical, magnetic, optical, biocompatible or decorative characteristics. When plasma is used as a processing medium, the field is known as Plasma Surface Engineering. The main techniques used in surface engineering can be synthesized as surface quenching (induction, laser or electron beam), surface alloying, thermochemical treatments, coating and ion implantation.

Each technique produces surface layers with specific characteristics. Combination of these basic treatments, with the aim to produce surface layers with improved properties in comparison with those obtained by each treatment applied individually, appears as a current trend in surface engineering.

A schematic representation of the main surface engineering techniques, including combined treatments is shown in Fig. 1. These techniques will be discussed below.

a) By surface quenching (hardening) a hard layer is produced at the surface of the component by phase transformation only, without addition of any other element. This transformation involves heating up of the component surface to a determined temperature followed by a fast cooling. The heating up can be achieved by induction (high frequency), laser or electron beam. In the last two cases the fast cooling occurs by dissipating the energy deposited into the surface layer in the core.

b) The concentration of the alloying elements of a component can be increased at the surface for a depth of up to 1 mm by laser alloying/dispersing. By this way, the core properties remain unchanged, while the surface characteristics are improved in terms of hardness, resistance at oxidation to elevated temperatures, wear and fatigue resistance. This treatment involves the laser-heating of the surface up to melting temperature of the substrate and the addition of various materials like W, Cr, WC, TiC, Cr_3C_2, SiC, etc. [1 – 5]. The additive materials can be introduced via slurry (paste) deposited on the surface prior to laser processing or by injection of the powder, together with a protective gas (Ar), into the melted spot. If the added material is melted during the process, an alloying phenomenon occurs. Some materials with high melting temperature, like TiC, are only dispersed into the substrate matrix. The fundamental advantages of laser surface treatment in alloying and dispersing processes can be summarized as follows: (i) local, selective treatment of parts, (ii) low thermal stress and consequently insignificant part distortion, (iii) creation of wear and fatigue resistant surface layers designed to withstand the intensive mechanical and thermal stresses, (iv) exact control of the temperature-time cycles during laser treatment, (v) wide range of applications. The types of laser used for surface treatment are usually Nd:YAG laser (λ = 1.06 μm) and High Power Diode Laser (HDL) (λ = 0.8-0.9 μm) with power in the range of 1 – 6 kW. The primary advantages of these types of lasers in comparison with CO_2 laser are the higher level of absorption (A Nd:YAG or HDL $\approx$ 20-35 %, A CO_2 < 10 %) and the possibility of flexible beam guiding and beam shaping via optical fibbers. In addition, HDL has a lower investment cost in comparison to both Nd:YAG and CO_2 lasers.

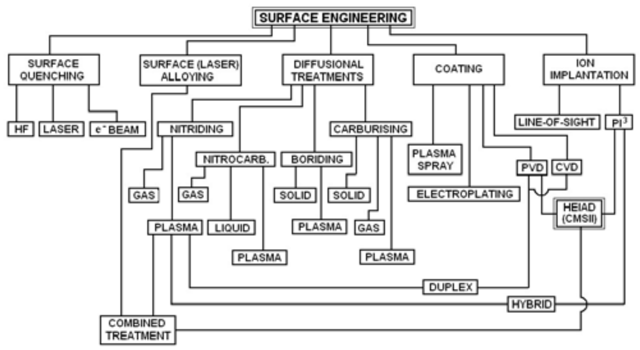


Fig.1. Schematic diagram of the main surface engineering techniques.

c) Diffusional or thermochemical treatments involve diffusion penetration of non-metallic elements like N, C or B into the substrate and formation at the surface of hard compounds like nitrides, carbides, nitrocarbides or borides. Usually, the case depth and the hardness of the surface layers produced by these techniques are in the range of 0.02 – 2.0 mm and 350 – 1100 HV respectively, depending on the type of treatment, type of substrate and processing parameters.

d) In a coating process a hard layer is produced by various means and it is deposited on the surface without affecting the substrate properties. By plasma spray, relative thick coatings of 0.1 – 0.5 mm are deposited using powder material of various compositions. The process can be run at atmospheric pressure (PS) or under vacuum conditions (VPS). Typically, the coatings deposited by plasma spray have a certain level of porosity, so the coating density hardly exceeds 90 % of the density for the bulk material. Electroplating is the technique currently used at the industrial scale for anti-corrosive protective coatings such as Ni, Cr, Cd, etc. The application area of the coatings deposited by PVD (Physical Vapor Deposition) and CVD (Chemical Vapor Deposition) techniques covers many fields such as: protection against wear and corrosion, tribology, biomedical applications, coatings with special optical, magnetic, electrical or thermal properties, decorative coatings, etc. Depending on the particular application, the thickness of these coatings ranges between a few tens of nm and ~ 50 μm. The main PVD techniques can be summarized as follows: thermal evaporation, ion plating, cathodic arc evaporation, magnetron sputtering and ablation (PLD – Pulse Laser Deposition and EBA – Electron Beam Ablation). These techniques can be non-reactive, when the coating material is melted, sputtered or ablated and then directly deposited on the substrate or reactive, when the coating material is a result of the chemical reactions occurring in the plasma between the melted, sputtered or ablated material and the reactive gases introduced into the deposition atmosphere (nitrogen, hydrocarbons, etc.). As far as concern CVD techniques, the coating material is always produced by chemical reactions occurring between the constituents of the treatment atmosphere ($TiCl_4$, BCl_3, N_2, C_6H_6, etc.).

e) The ion implantation technique introduced in 1960's for doping semiconductors has been later developed for surface modification of materials with the aim to improve their wear, corrosion, tribological or biocompatible performances [6]. Since 1987, the conventional line-of-sight ion implantation technique has been replaced for these applications with a much cheaper method named initially Plasma Source Ion Implantation (PSII) [7, 8, 9] and then Plasma Immersion Ion Implantation (PI^3) [10]. In this case, the components to be implanted are insulated suspended into the processing chamber, where plasma is produced by electron emission of hot filaments, RF or ECR discharges. The components are negatively biased with respect to the chamber wall using a high voltage pulse generator. Typical voltage is in the range of 30 – 70 kV. The positive ions (N or C) are accelerated by the plasma sheath and implanted into the surface of the components. The penetration depth of the implanted ions is usually in the range of 0.1 – 0.2 μm.

2. Hybrid plasma processing technique

Significant improvements in wear, corrosion and fatigue resistance of the steel components can be produced by plasma nitriding. Unfortunately, the application area of this technique is very limited for steels with low tempering temperature like cold working steels, or stainless steel. In the case of stainless steels, the treatment at normal temperature (520 – 550 °C) leads to formation of CrN and to loose of the corrosion resistant properties. Decreasing of the treatment temperature below 480 °C improves the corrosion resistance, but dramatically decreases the productivity. On the other hand, ion implantation is considered to be a low temperature process (100 – 200 °C), but the implanted depth is only 0.1 – 0.2 μm. This seems to be too little for many industrial applications. As a result of the interaction between an implanted ion and substrate matrix, the ion energy is progressively shared with the atoms of the lattice, leading to a local heating at atomic dimensions. The process is called atomic scale heating (ASH) and it is accompanied by extremely fast cooling rates of about 10^{14} K/s [11]. The ion bombardment is a strongly non-equilibrium process and it can induce formation of special structures, which can not be produced by other means [12]. By applying the PI^3 technique to a silicon sample at a discharge voltage of 25 kV, nitrogen concentrations of up to 30 wt.% have been obtained [7].

In order to increase the penetration depth of the implanted ions the processing temperature during PI^3 was increased. The idea was to combine ion implantation with a diffusion process. As a consequence, the depth of nitrogen penetration increased up to 14 μm at 520 °C, but the specific characteristics of the implanted layer disappeared. For stainless steel treated at a temperature over 500 °C the structure of the surface layer produced by PI^3 is similar to that obtained by plasma nitriding at the same temperature [13]. In other cases, the nitrogen profiles obtained by plasma-immersion nitriding show depths of the nitrogen-rich phases of up to 50 μm and 15 μm in stainless steel at 380 °C and aluminium at 500°C, respectively [14]. Very good results have been obtained in Brazil caring out PI^3 process with N_2 at temperatures between 300 °C and 450 °C [15]. High speed steel tools such as rollers (Φ 30 mm), hammers for rivets (Φ 7 × 30 mm), punches for high temperature working (Φ 12 × 40 mm) have been processed at the following parameters: $U = 12$ kV, $\tau = 60$ μs, $f = 1.5$ KHz, $p = 2\times10^{-3}$ mbar. The tool lifetime increased for these tools by factors ranging between 4.4 and 70.

3. High energy ion assisted deposition

Ion beam assisted deposition (IBAD) is a well known technique in which physically deposited coatings are bombarded, either concurrently or in a multiply sequential process, with a beam of energetic ions [6]. Usually, the energy of these ions is in the range of 100 – 1000 eV. The main improvements of the ion bombardment produced on the coating performances are briefly discussed below.

(i) Ion bombardment, in the early stages of the deposition removes the superficial oxides or other contaminants from the substrate. Later, after the deposition of the first layers, it is an efficient instrument to intermix the deposited atoms with the atoms of the substrate. Sputtering and partial re-deposition of the sputtered atoms are the main processes producing the mixing zone between the substrate and coating, which is responsible for significant improvement of adhesion.

(ii) Low energy ion bombardment causes a considerable densification of the coating [16]. Usually, physically deposited films contain many vacancies and pores due to the limited surface mobility of the deposited atoms. Ion bombardment increases this mobility and displaces the atoms into nearby vacant sites. The ion assisted deposited coatings can achieve the bulk density and be pore free.

(iii) By the delivered energy, the ion bombardment controls the growth mechanism of the film. It can restrict the grain growth allowing the formation of nano-crystalline structures. The size and the orientation of the grains can be controlled by the energy and flux of the bombarding ions [12].

On the other hand, the PI^3 process involves a high voltage pulse discharge superposed over plasma generated by various techniques. If this technique is a discharge producing metallic atoms by sputtering or evaporation, the deposition and ion implantation processes occur simultaneously. A review of this combination, which has been denoted as PI^3&D and covers the whole family of plasma immersion processes, has been quite recently done by Anders [17]. The concepts of metal implantation and metal deposition and implantation with or without reactive gases are analyzed. The main vapour sources used for this combined process are cathodic vacuum arc and magnetron. DLC (diamond-like carbon) and metal carbides have been produced by using filtered cathodic vacuum arcs in combination with PI^3. It was demonstrated that film morphology and microstructure, multilayer structures and interface can be widely tailored by adjusting the ion energy and other process parameters [18]. In other experiments [19], TiN films were deposited by cathodic vacuum arc and PI^3 at 20 – 40 kV / 20 μs pulse duration. XRD analyses have shown a strongly (200) preferred orientation, while for the coatings deposited with a DC bias the crystal preferred orientation was (111) and (220). Quite recently, the PI^3 process was associated with a Metal Plasma Electron Evaporation Source (MPEES) producing Cr and Ti implanted coatings [20]. The system starts with argon plasma to evaporate and ionize metal atoms. Once the system is stabilized, argon is turned off and the metal plasma sustains on its own. This plasma is used as an ion source for PI^3 process, but at the same time a deposition occurs.

A special attention will be further paid to the combination between magnetron plasma and ion implantation using a high voltage pulse discharge. As it is reported in the literature, this technique has already reached the industrial phase in China. Cu ions have been implanted into an Ag substrate using an industrial prototype DLZ-01 PSII implanter with a radio frequency source for enhancing plasma production and four unbalanced magnetron (UBM) cathodes for producing metal atoms [21]. Another facility with two unbalanced magnetrons of 0.85 kW each and a high voltage generator ($U_{max} = 50$ kV, $I_{max} = 4$ A, $\tau = 1\div1000$ μs, $f_{max} = 3$ kHz) was build in Germany [22]. Using this equipment TiN coatings of 1 – 2 μm, were deposited on 100Cr6 ball bearing steel substrate and their properties were investigated. The results show a drastically decrease in hardness from 20 GPa to ~ 4 GPa by increasing the high voltage from 2.5 kV to 10 kV. With further increase in voltage the hardness remains at the same level. SEM analyses indicated a denser structure of the coatings deposited at 5 kV in comparison with those deposited by conventional magnetron sputtering with a bias voltage of – 50 V. At the same time, the densification of the coatings decreases with increasing the high voltage over 5 kV. Another interesting combination between magnetron sputtering, ion implantation and ECR discharge is reported in the literature [23]. The magnetron power is ~ 2.5 kW for a target of 100 mm in diameter and the high voltage generator can provide 80 kV for pulse duration of 15 μs and a frequency of 100 Hz. The plasma concentration is increased by an ECR discharge at 2.45 GHz and 1.2 kW. A Ti evaporation device is available as well. A 70 nm thick TiN film was produced on a Si substrate by titanium deposition and subsequently treated by PI^3 in nitrogen.

During the last 5 years systematic investigation has been carried out at the National Institute for Laser, Plasma and Radiation Physics in Bucharest in the field of hard coating deposition by a combined technique between magnetron sputtering and ion implantation (CMSII). A schematic representation of the equipment is shown in Fig. 2. The deposition chamber, made of stainless steel with water cooled walls, has an inner diameter of 300 mm and a height of 420 mm. On the bottom plate a magnetron with a target diameter of 75 mm is mounted. On the top lid of the chamber there is a ceramic insulator designed to sustain 100 kV. The components to be treated are positioned in the chamber via a rotating planetary system which ensures a uniform coating. The load is biased with negative pulses of 20 – 70 kV, 20 μs and 25 Hz. A DC bias of – 85 V is applied between pulses. Mass flow controllers have been used to introduce argon and reactive gases (N_2, C_2H_2, etc.) into the deposition chamber.

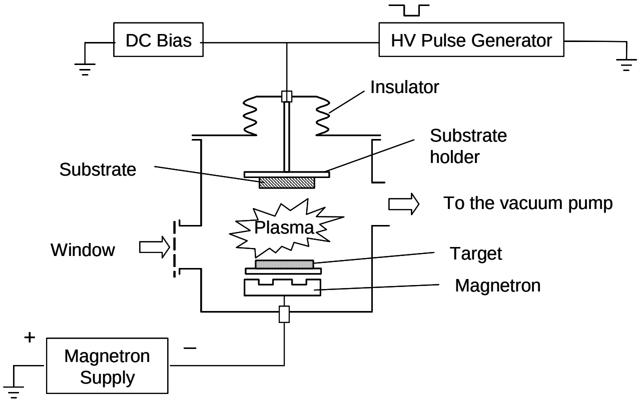


Fig. 2. Schematic representation of the CMSII set-up.

The advantages of the ion assisted deposition methods discussed at the beginning of this section are valid for CMSII technique too. Intermixing zones between coating and substrate of 5 – 7 μm, which leads to a significant improvement of adhesion, are usually obtained. In addition, the high energy ion bombardment produces a stress relief at the interface and within the coating. Due to this effect, hard coatings with a thickness of 10 to 50 μm have been obtained. Actually, CMSII method has been developed to produce relative thick coatings in the range of 10 ÷ 50 μm.

It should be noted that the coating during its growth is periodically bombarded with energetic ions. At a frequency of 25 Hz, the duration between two subsequent pulses is 40 ms. For a deposition rate of ~ 4 μm/h, the thickness of the deposited layer within 40 ms is ~ 0.4 Å (0.04 nm). This is less than one atomic layer, but for 1 s, a few atomic layers are deposited. If the penetration depth of the energetic ions under CMSII conditions is ~ 0.1 μm, this thickness is reached after 90 s. During this time, 2250 pulses have been applied. This simple calculation demonstrates that the energetic ions act at the atomic level and they are continuously and uniformly implanted into the growing layer [24]. The method has a high flexibility. By changing the magnetron target and the reactive gases a large variety of coatings can be obtained. A great research effort has been done to produce and investigate the nano-composite coating nc-Ti_2N/nc-TiN (nano-crystalline Ti_2N/ nano-crystalline TiN), which was reported in the literature for the first time in 2005 [25]. A few characteristics of this type of coating will be described below. As it can be seen in Fig. 3, its structure is featureless, extremely dense and pores free. TEM analysis (Fig. 4) revealed a nano-crystalline structure, composed of very fine crystallites, appearing like dots at a size of less than 10 nm. Selected Area Electron Diffraction (SEAD) analyses indicate the presence of Ti_2N as the dominant phase, but traces of TiN phase were also detected. Chemical composition and phase constitution of the nc-Ti_2N/nc-TiN coating determined by Optical Glow Discharge Spectrometry (OGDS) and X-Ray Diffraction (XRD) respectively are shown in Figs. 5 and 6 in comparison with a TiN coating deposited by standard magnetron sputtering (SMS) [26]. Both OGDS profiles (Fig. 5a) and XRD pattern (Fig. 6a) indicate for the coating deposited by CMSII technique a Ti_2N dominant phase. The coating deposited by SMS has clearly a TiN structure. The larger mixing zone produced at the coating-substrate interface by CMSII in comparison with SMS can be clearly seen in Fig. 5. The hardness and the deposition rate of the nc-Ti_2N/nc-TiN nanocomposite coatings deposited by CMSII strongly depend on the nitrogen flow rate, which is the key factor in optimizing the process technological parameters. This dependence is shown in Fig. 7. The deposition rate depends not only on the nitrogen concentration in the treatment chamber, but also on the state of the target. The normal deposition rate is ~ 4.5 μm/h. Although coatings with a thickness of 52 μm have been obtained (Fig. 8), currently 10 ÷ 15 μm was applied on high speed steel and cemented carbides cutting tools for testing (Fig. 9). Under industrial conditions, their lifetime was increased by a factor ranging between 2 and 2.5.

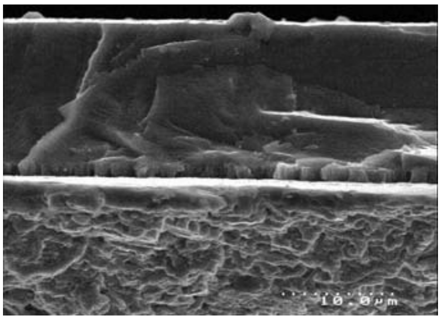
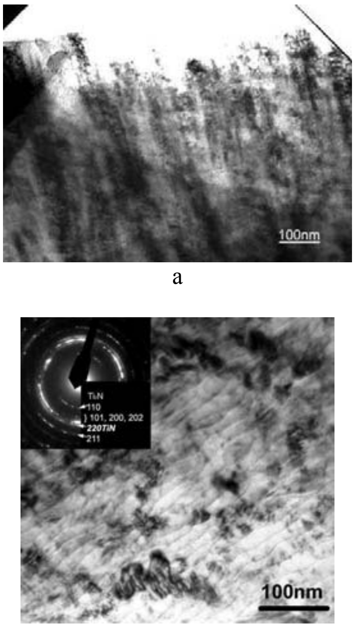


Fig. 3. SEM micrograph of the nc-Ti_2N/nc-TiN coating deposited by CMSII on HSS substrate.



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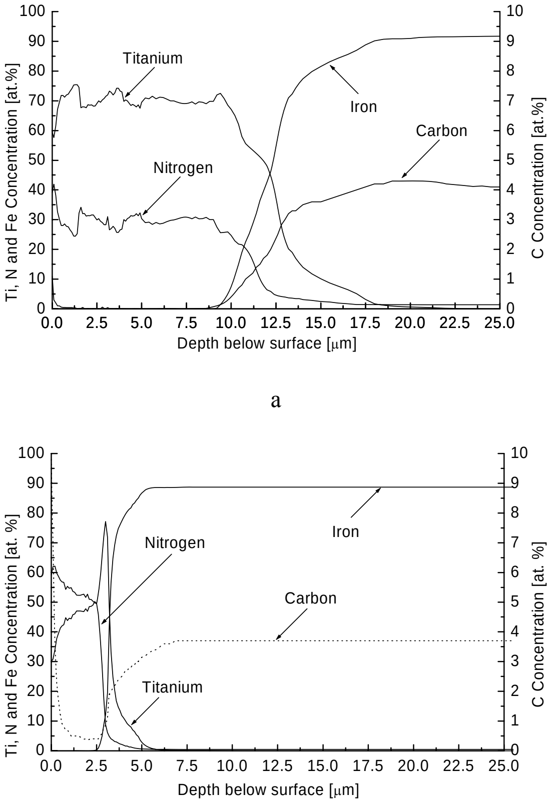
b

Fig. 4. Cross-sectional TEM microstructure (a) and plane view TEM microstructure with corresponding SAED pattern (b) of the nc - Ti_2N/nc - TiN coating deposited by CMSII.



a

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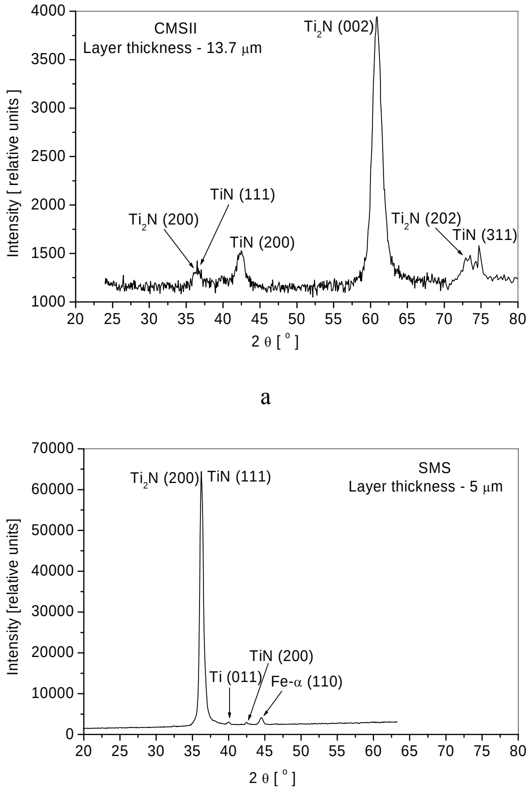
Fig. 5. Depth profiles of Ti, N, Fe and C for nc-Ti_2N/nc-TiN (a) and TiN (b) coatings.



a

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Fig. 6. XRD patterns for nc-Ti_2N/nc-TiN and TiN coatings.

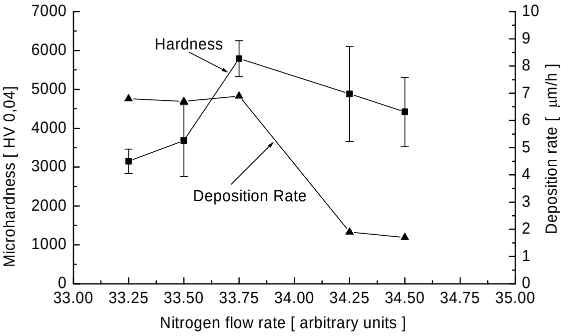
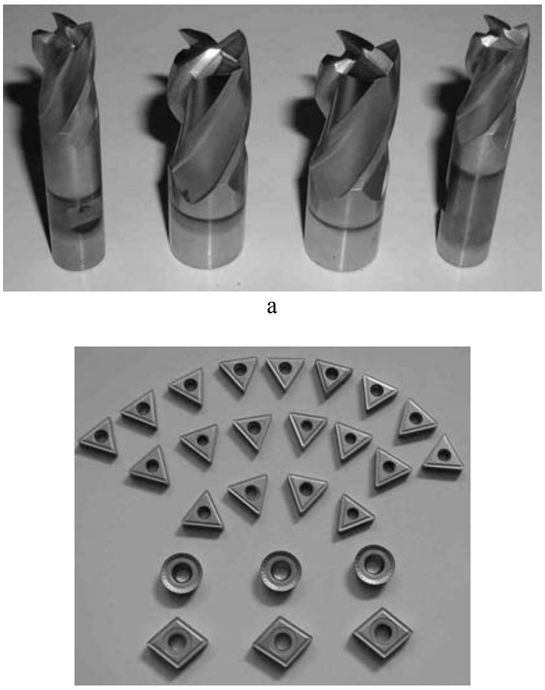


Fig. 7. The influence of the nitrogen flow rate on the microhardness and deposition rate of the coatings produced by CMSII technique.

Fig. 8. Micrograph of a nc-Ti_2N/nc-TiN nanocomposite coating with a thickness of 52 μm deposited on plain carbon steel.



a

b

Fig. 9. High speed steel milling cutters and WC inserts coated with nc - Ti_2N/nc-TiN nanocomposite coating by CMSII technique.

This type of coatings seems to have the best performances in cutting non-ferrous materials like bronze, aluminium alloys and possible wood. Very recently, CMSII technology has been successfully applied for coating with 10 μm tungsten CFC (Carbon Fiber Composite) substrates. The CFC tungsten coated tiles will be used as first wall in particular areas of the plasma fusion reactor. The W coatings deposited by CMSII technology exhibited a much higher resistance at intense heat fluxes in comparison with other coatings deposited by PVD and CVD techniques.

4. Duplex treatment

Plasma nitriding is a thermochimical treatment, which generally produces relative thick layers (0.3 – 0.8 mm), but the surface hardness, depending on the quality of the steel, does not exceed 1.400 HV0.1. On the other hand, by coating techniques, layers with hardness of 2.000 – 4.500 HV0.05 and thickness of 2 – 15 μm can be usually obtained. A surface layer produced by a combination between these two procedures could provide a very good wear and corrosion resistance due to the hard coatings and at the same time a very good fatigue resistance and load bearing capacity due to the nitrided layer. This combined technique is usually called in the literature duplex treatment. One of the problems in applying this treatment is the adhesion between the coating and the compound layer produced by plasma nitriding. This aspect was investigated in details by Sun and Bell [27]. The experiments were carried out with the nitriding steel En40B (composition in wt%: 0.23 C, 3.21Cr, 0.50Mo, 0.03Al, 0.02V, 0.52Mn, 0.18Ni, 0.08Si, 0.014S, 0.006P), which was plasma nitrided in various regimes and coated with 1 – 4 μm TiN, CrN and (TiAl)N by magnetron sputtering. Prior to coating, the samples were prepared by three different procedures: standard chemical cleaning including ultrasonic cleaning, dry micro-blasting and slight grinding. When only standard cleaning was applied, a “black” layer of ~ 1.5 μm was formed between the coating and compound layer. This “black” layer is relatively soft (400 – 500 HV), contains mainly α-Fe and appears to be produced by the decomposition of the compound layer during the deposition process. It seriously affects the performances of the duplex layer. This problem does not appear when dry micro-blasting or slight grinding was applied on the nitriding layer before coating. Wear test results indicated an improvement of the tribological and load bearing properties of the duplex layer in comparison with layers produced by the individual treatments by a factor of 4 – 8. The quenched and tempered components are worn via surface and subsurface plastic deformation, while the wear mechanism of the plasma nitrided components is dominated by the oxidation of the contact surfaces and the subsequent removal of the oxide products. A thin TiN coating deposited on nitrided surface is effective in reducing the wear rate of the nitrided steel [28]. The adhesion of the TiN coating to the plasma nitrided substrate, in particular the presence of oxides at this interface, was investigated by other authors as well [29].

The duplex treatment is usually applied to solve the wear problems in particular cases. A few examples are given below. In the field of cold forming tools the TiN, TiB_2, TaC and DLC coatings have been tested on pre-nitrided surfaces, the working material being austenitic stainless steel [29]. Although the TiN and TiB_2 coatings showed the best wear resistance, they are brittle and posses a high tendency to pick up work material. From the point of view of tool life as well as workpiece surface quality, the DLC coating with its excellent anti-sticking properties and suitable wear resistance was the best solution. TaC is a good option too. The plasma nitriding can be also associated with PACVD, the treatment being carried out in the same cycle with the same equipment [30]. The best results for adhesion of Ti(B,N) and TiB_2 hard coatings to the nitrided surface were found on substrates with Fe_4N compound layers or with only diffusion layers. The tests performed in aluminium or magnesium die casting, and aluminium extrusion and forging applications showed a good surface quality of the products and an extended lifetime of the tools. Similar results have been obtained by the same duplex technique when a TiCN coating has been applied on a hot working die made of AISI H13 [31]. The best adhesion between a TiBN coating produced by PACVD and the plasma nitrided hot-working steel X38CrMoV5-1 was found to be with a Fe_4N compound layer [32].

Fig. 10. Turning cutters coated with nc-Ti_2N/nc-TiN nanocomposite coating.

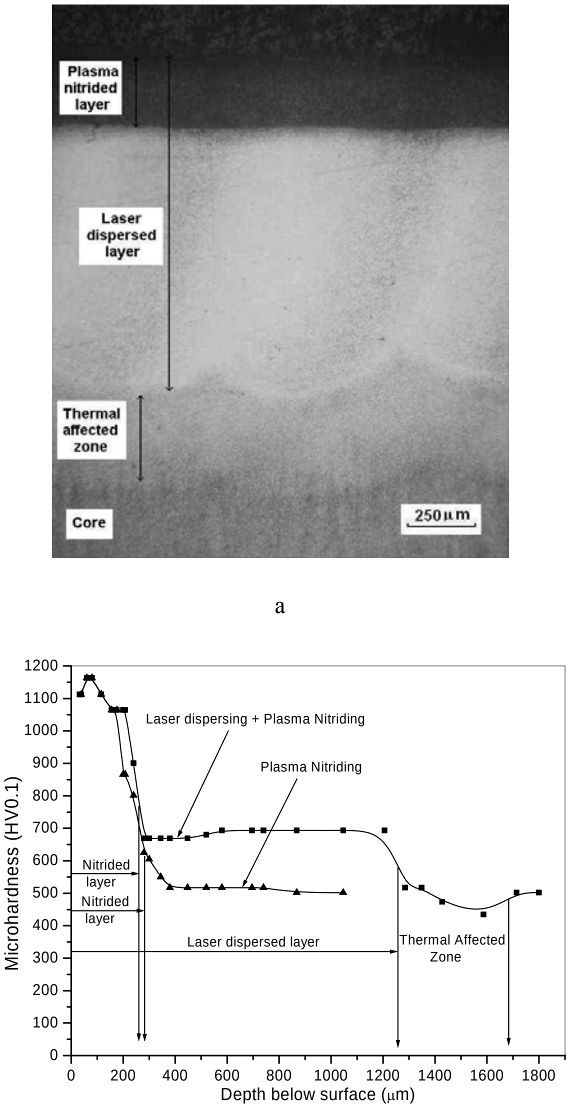
Besides cold and hot forming tools, cutting tools is another field of application for duplex treatment. Cutting knives used in wood machining, made of 32CrMoV13 low alloy steel, were plasma nitrided and coated with ZrBN [33]. The tests indicated an increase of the tool lifetime by a factor of 6.5. The turning cutters shown in Fig. 10, made of high speed steel with a standard hardness of 950 HV, have been used to make internal grooves with a deep of 7 mm and a width of 1.5 – 3 mm, in big rings (diameter of

~ 1500 mm) made of bronze B11G21. Only one groove was made with each cutter before re-sharpening. By applying a plasma nitriding treatment, a layer with a case depth of 22 μm and a surface hardness of ~ 1.500 HV0.1 was produced. With this treatment, each cutter could be used to cut 3 grooves before re-sharpening.

On plasma nitrided cutters, a nano-composite coating nc-Ti_2N/nc-TiN with a thickness of 8 μm was applied by CMSII technology. The number of grooves cut with each cutter treated by duplex technique increased to 12. The coating hardness was in the range of 3,000 – 3,200 HV0.1.

5. Laser alloying/dispersing and plasma nitriding

In some applications like forging, the die surface is subjected to a very intense mechanical and thermal stress. The main phenomena which limit the tool lifetime are: plastic deformation, cracks, abrasive wear, surface oxidation and sticking of the forged material to the die surface. The conventional surface treatments of the forging dies are nitriding (plasma or gaseous) or salt bath nitrocarburising. In the first case a compound layer of 4 to 8 μm and a diffusion zone of ~ 0.3 mm are produced. The case depth of the nitrocarburised layer is usually ~ 50 μm. Due to the hard working conditions, the die surface layer requires a very good wear and fatigue resistance. Sometimes, the nitrided layer of ~0.3 mm is insufficient to provide a long lifetime of the die. In order to solve this problem and to increase the durability of the forging dies, a combined treatment between laser alloying/dispersing and plasma nitriding has been developed. It has been experimentally applied on W1.2344 steel using TiC powder. The hardness of the surface has been increased from ~500 HV to ~650 HV for a depth of ~1.1 mm. Below the dispersed zone there is a thermal affected zone of ~ 0.4 mm where the hardness is about 50 HV lower than the core hardness. After laser dispersing, the treated area is ground and the die is plasma nitrided. The micrograph and the microhardness profile of the surface layer produced by this combined treatment are shown in Fig. 11. For comparison, the microhardness profile of the plasma nitrided layer produced on the same sample in the non-dispersed area is also shown in Fig. 11b. As it can be seen, there is no significant difference in the microhardness profiles for plasma nitrided layer with or without laser dispersing, but laser dispersing produces below the nitrided layer a zone of ~ 0.8 mm with a hardness of ~ 650 HV, which is expected to improve significantly the fatigue resistance of the die and consequently its lifetime. The tests on real forging dies are on progress now. There is no reference in the literature concerning this type of treatment so far.



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b

Fig. 11. The micrograph a) and the microhardness depth profiles b) of a W1.2344 steel sample treated by laser dispersing and plasma nitriding.

6. Conclusions

In this paper, only the main combinations between basic treatments have been described. These are diffusional treatments and coating, diffusional and ion implantation, coating and ion implantation, laser alloying/dispersing and diffusional treatments. Other options are possible as well. Many combined treatments have been developed at the laboratory scale only. Their application at the industrial level requires relative large investments. The combined treatment should be applied from the beginning to the end in the same industrial unit, which has to be big enough to have plasma nitriding, PVD or CVD and ion implantation equipment. This is not very simple, but such companies started to appear on the market. The acceptance of the combined treatments is a matter of price/performance.

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