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Influence of Ion Current Density on the Properties of Vacuum Arc-deposited TiN Coating

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Influence of ion current density on the thickness of coating deposited in the vacuum arc setup has been investigated. A planar probe was used to measure the ion current density distribution across plasma flux at a distance of 250 mm from the plasma duct exit. The current density from 20 to 50 A/m² was obtained, depending on the probe position relative to the substrate center. TiN coatings were deposited onto cutting inserts placed at different locations on the substrate, and SEM technique was used to characterize surfaces of the coatings. It was found that low-dense coatings were formed at the decreased ion current density. A quantitative dependence of the coating thickness on the ion current density in the range of 20 to 50 A/m² were obtained for the films deposited at substrate bias of 200 V and nitrogen pressure 0.1 Pa. The results may be useful for controlling ion flux distribution over the large substrates.

Keywords: DC discharges, Ion-assisted deposition, Thin films.

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1. INTRODUCTION

Plasma reactors are widely used in industry for etching, deposition and modification of thin films and nanostructures [1-3]. Ion current density is a key parameter to be controlled for maintaining uniformity of the wafer treatment evenly from center to edge [4], and for affecting the quality of growing film by varying current density in the particular area of the wafer [5-8].

It is known that structure and properties of the films grown at low ion energy and strong ion fluxes differ from those of the films deposited at high ion energy but low ion flux [5, 9]. The film growth temperature is also influenced by the ion current and in turn, affects the film properties [10, 11]. The main features of the influence of ion current density to the properties of a processed surface are qualitatively described by the structure zone diagram (SZD), but SZD cannot be directly used to characterize materials a researcher is interested in [12]. Any combination of substrate, film material, and deposition conditions represents a unique system that is not adequately described by SZD and should be treated experimentally.

Recently, a method of the ion current density control was reported suitable to regulate the ion flux extracted from various types of plasma reactors, where the magnetic field is used to guide the plasma from a source to a substrate: arc sources, unbalanced magnetrons, ECR and helicon wave plasma generators [13-16]. In this paper we investigate the influence of the ion current density on the formation of dense coatings on the substrates in the vacuum arc deposition setup. The motivation is to determine the limits for the ion current density that are acceptable for the formation of serviceable TiN coatings on a surface of cutting tool inserts. The results may be suitable at determining the deposition modes for other applications.

2. EXPERIMENTAL PART

The experimental setup is shown schematically in Fig. 1. It includes a vacuum arc plasma source and a planar probe for measuring the radial distribution of an axial component of the ion flux. The plasma source was fitted with a water-cooled truncated cone-shaped titanium cathode and a tubular water-cooled anode. The cathode cone was 60 mm long, with a 50 mm diameter upper surface and base diameter of 60 mm. The anode had a 210 mm inner diameter and a length of 200 mm. A guiding coil was mounted on the anode, so the anode was used as a plasma duct. The plasma source was mounted on a flange of 500 mm diameter, 500 mm long cylindrical vacuum chamber. The dc arc current, $I_a = 100$ A, was applied between the cathode and the anode, which was grounded.

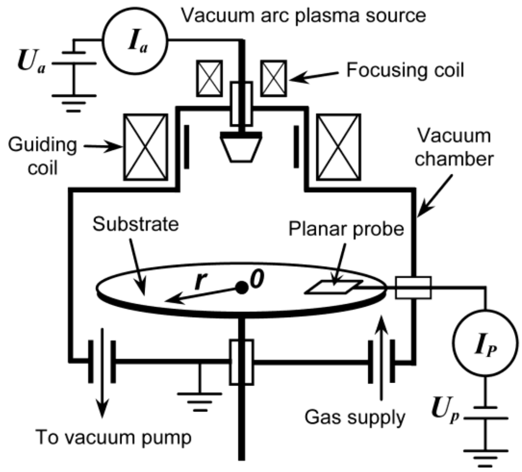

Fig. 1 – Experimental setup

Focusing and guiding coils generated an axial magnetic field in the plasma source. The focusing magnetic field B_f (0.03 T at the center of the focusing coil) was used to retain cathode spots on the cathode face. The guiding magnetic field B_g (0.016 T at the center of the guiding coil) was used to guide the plasma beam towards the substrate.

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A disk-shaped substrate made of nonmagnetic stainless steel was installed in the vacuum chamber at a distance of 250 mm from the plasma duct exit in such a way that the substrate and plasma duct (anode) axes of symmetry coincided. The substrate diameter and thickness were 400 mm and 8 mm, respectively. The substrate was under negative potential of 200 V relative to the grounded walls of the vacuum chamber. An automatic gas supply system maintained nitrogen pressure of 0.1 Pa in the chamber. The pressure was measured with the help of thermocouple vacuum gage and ionization gage.

A planar probe was used to measure the ion current density distribution in the axial plasma flux as a function of probe position over the substrate (r axis in Fig. 1). The probe was a $50 \times 48 \times 0.5$ mm current-collecting plate made of polished nonmagnetic stainless steel with a high-temperature insulator on one sides. The probe was connected to the power supply via a separate ammeter. When the vacuum arc plasma source was on, the voltage drop between the probe and anode was 200 V, so the saturated ion current was collected [17]. The duration of each experimental run was 2 s.

The cutting tool inserts (16×16×5 mm, 89 % WC + 15 %(Ti+Ta)C + 6 % Co) were placed on the substrate in points with coordinates $r = 0$, 40, 70, 100, 130, and 160 mm to deposit TiN coating on the cutting surfaces. Before deposition, the inserts were cleaned and heated by ion flux at the bias potential of 1.5 kV for 8 minutes. The deposition time was 30 minutes. After deposition, side surfaces of the cutting inserts were polished, and SEM images of the coating were made to determine the coating thickness and morphology.

3. RESULTS AND DISCUSSION

The dependence of the ion current density distribution on radius r (see Fig. 1) was taken during stable arc operation. Fig. 2 shows the results obtained using the planar probe.

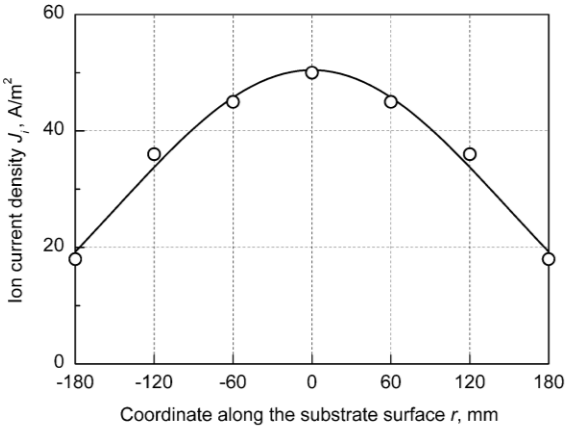

Fig. 2 – Ion current density distribution as a function of coordinate along the substrate surface

This graph also illustrates the results of the approximation of the experimental data points which were obtained by averaging 10 measurements. The experimental data were approximated by the Gaussian distribution function, and the following expression is obtained:

$$J_i(r) = -9.8 + 60.242 \exp\left[-\left(\frac{r}{210.65}\right)^2\right], \text{ (A/m}^2\text{)} \quad (3.1)$$

where r is the coordinate along the substrate surface, mm.

The distribution of the experimentally determined thickness of the coating deposited on the cutting inserts is shown in Fig. 3.

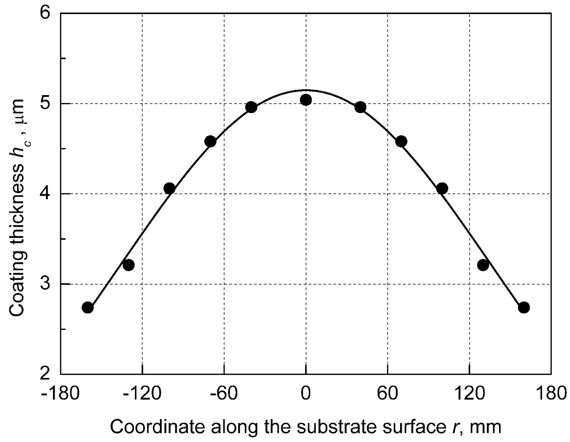

Fig. 3 – Coating thickness distribution as a function of coordinate along the substrate surface

The thickness data obtained were also approximated by the Gaussian distribution function:

$$h_c(r) = 0.2 + 4.945 \exp\left[-\left(\frac{r}{193}\right)^2\right]. \text{ (μm)} \quad (3.2)$$

Relative ion current distribution and coating thickness were also calculated, and the results are presented in Fig. 4.

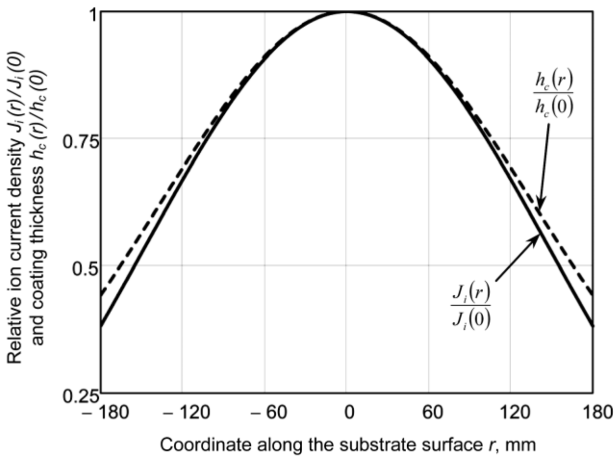

Fig. 4 – Relative ion current density and coating thickness as a function of coordinate along the substrate surface

SEM images of the coatings deposited on the cutting inserts at different locations along the substrate surface are shown in Fig. 5.

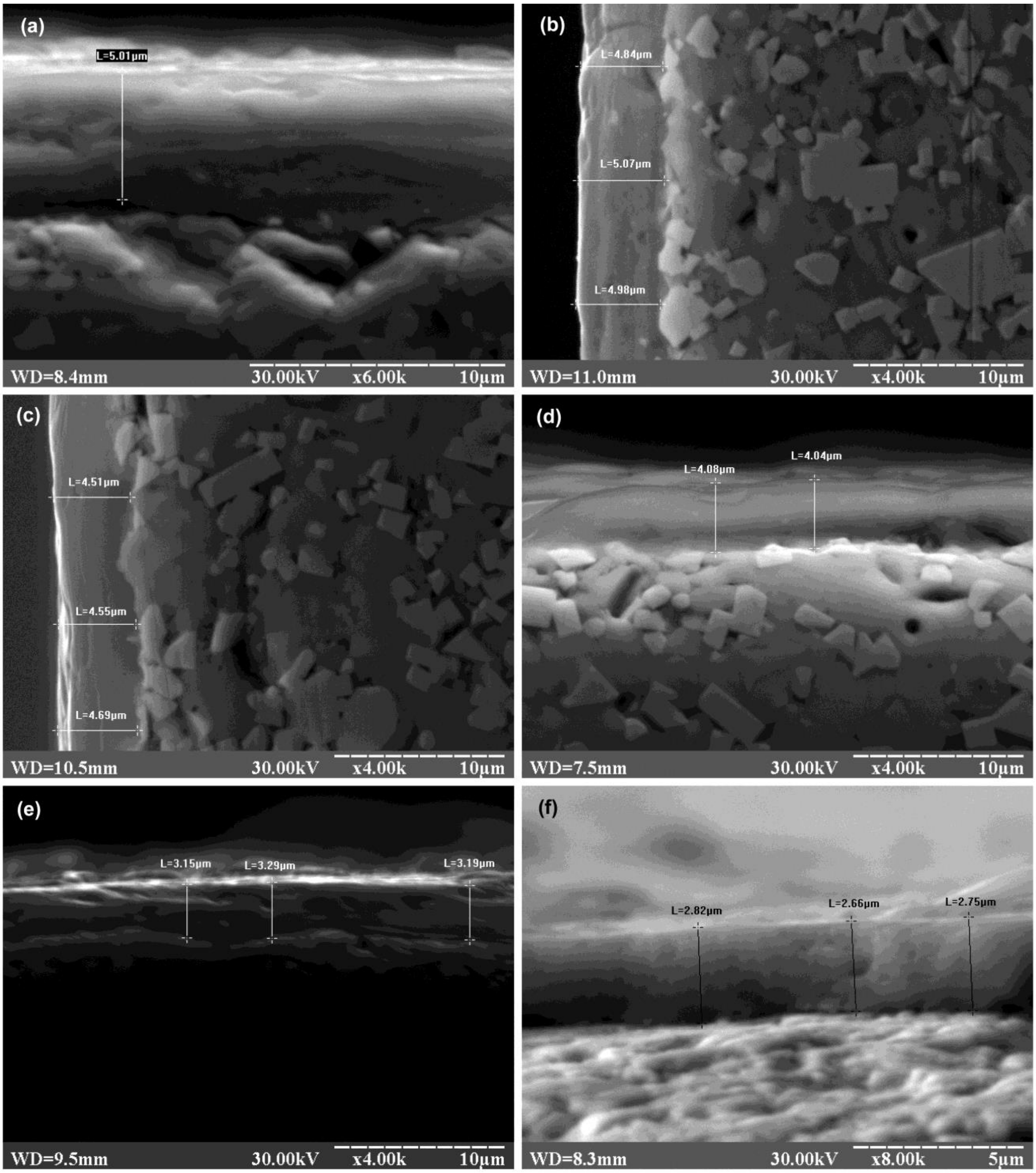

Fig. 5 – SEM images of the coatings deposited on the cutting inserts at different locations along the substrate surface for deposition time t = 30 minutes: a - r = 0 mm; b - r = 40 mm; c - r = 70 mm; d - r = 100 mm; e - r = 130 mm; f - r = 160 mm

The thickness of the coating is related to the ion current density by use of equations (3.1) and (3.2):

$$h_c(J_i) = 0.2 + 4.945\left(\frac{J_i + 9.8}{60.24}\right)^{1.184}. \text{ (μm)} \quad (3.3)$$

Assuming that the non-linearity of the above dependence results in the formation of a low-dense (porous) coating, the influence of the ion current on the coating structure may be estimated as follows.

Let us approximate the dependence of the thickness of the dense coating on ion current density by equation of the tangent line to the curve (3.3) drawn through the point of maximum ion current density, where the most dense coating is formed (i.e. 50 A/m^2, according to Fig. 2):

$$h_{c0}(J_i) = 0.097(J_i - 50) + 5.102 \text{ . (μm)} \quad (3.4)$$

A relative volume of the coating can be estimated by the expression $\left(h_c(J_i)/h_{c0}(J_i)\right)^3$ which is plotted in Fig. 6, together with values $h_c(J_i)$ and $h_{c0}(J_i)$.

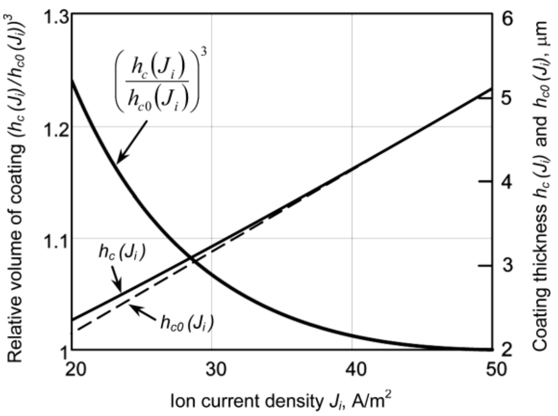

Fig. 6 – Relative volume of coating as a function of ion current density and dependence of the coating thickness in linear and non-linear approach

The coating porosity is calculated as $\left(h_c(J_i)/h_{c0}(J_i)\right)^3 - 1$, and hence, an increase of the porosity with decreasing ion current density can be determined. This increase may be attributed to the lower substrate temperature at the deposition.

For the cutting inserts, a test by lathe machining of the stainless steel has proven the workability of the coating obtained at the ion current density not less then 30-32 A/m², which corresponds to the coating porosity of about 6 %. However, the acceptable level of the porosity and hence the minimum value of the ion current density can be varied for other applications such as decorative coatings.

4. CONCLUSION

Dependence of the coating thickness on the ion current density over the substrate immersed into the plasma flux extracted from the vacuum arc plasma source demonstrates non-linear behavior. Decreasing of the ion current density from the substrate center toward its edges results in deposition of more porous coating, which is consistent with the trends of the structure zone diagram. In our experiments, the ion current density decreased by 2.1 times ($r = 160$ mm) while the coating thickness decreased by 1.9 times only. From these data, the quantitative dependence of the thickness of TiN coating on the ion current density ranging from 20 to 50 A/m² was obtained for coatings deposited at substrate bias of 200 V and nitrogen pressure 0.1 Pa.

The results of this work can be used in the technological vacuum arc plasma setups with the controlled ion current density over the substrate. The results allow selecting the minimum value of the ion current density, and hence, maximum deposition area, to obtain uniform TiN coating over the large substrates for different coating applications (wear-resistant, corrosion-resistant, decorative etc.).

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