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Reprint of: Physical mechanisms of macroparticles number density decreasing on a substrate immersed in vacuum arc plasma at negative high-frequency short-pulsed biasing☆

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ABSTRACT

The objective of this investigation was to study the physical mechanisms of macroparticles (MPs) number density decreasing on a substrate immersed in a vacuum arc plasma.

It was found that negative repetitively pulsed biasing of the substrate significantly reduced the MPs content on surface. Several different physical mechanisms for the MPs decreasing have been identified. It was established that up to 10% of the MPs are repelled by the sheath electric field.

Reduction of MPs density by almost 20% is attributable to ion sputtering after 2 min of processing. It was found that enhanced ion sputtering, MPs evaporation on substrate surface, and even evaporation of MPs in a sheath, can take place depending on the cathode material and the irradiation parameters.

Introduction

A vacuum-arc plasma is characterized by the high degree of the ionization of products of cathode material erosion. This benefit provides the wide practical application of vacuum-arc plasma for different multifunctional coating deposition technologies [1–3]. The main disadvantage of vacuum-arc discharge, which considerably limits its applications, is the presence of significant amounts of microdroplets, often referred to as MPs. MPs have size 0.1–100 μm, and velocities from 1 m/s to 800 m/s [4,5]. The presence of MPs in the metal plasma leads to the creation of pores, and consequent degradation of homogeneity and properties of coatings, and a significant increase in their roughness.

A number of different MP filtering systems have been proposed and developed in order to obtain MP-free dense metal plasmas. Nevertheless, the transportation efficiency of vacuum arc plasma through such filters is low [6,7].

Many different approaches have been proposed and tested to decrease MP number density in the coatings [8,9]. The more interesting effects of the MPs number and surface density reduction exerted on the substrate during coating formation have been observed experimentally, and reported in Refs. [10–12]. The authors of this paper observed an MPs density reduction by 3–4 times with increasing DC negative bias potential up to $\varphi = -1000$ V on substrates immersed in the vacuum arc plasma.

In the study of these results in Ref. [13] an explanation of the observed effect was proposed. The authors suggested that it was possibly based on electrostatic repulsion of negatively charged MPs, by the sheath electric field near the biased substrate.

Schanin et al. [14] described investigation of the possible enhancement of the MPs reflection effect by increasing the temperature of plasma electrons and therefore increasing the MPs potential in the plasma. They used not only conventional vacuum-arc plasma, but also the gas-discharge plasma of low-pressure arc, which has a higher electron temperature. The authors of that work observed a decrease in the MPs surface density by several fold at the DC substrate bias up to −1000 V, after 10 min deposition of the coating. They have used the same physical model of MPs electrostatic repulsion to explain the effect of MPs density reduction on the sample surface.

This paper deals with the study of different physical mechanisms of MPs number density decrease on a substrate immersed

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in vacuum arc plasma at negative high-frequency short-pulsed biasing.

The experimental setup and methodology of research

An investigation of the influence of high-frequency short-pulse negative substrate biasing on the behavior of vacuum-arc MPs near and on substrates was carried out using the experimental setup described in Ref. [15]. The vacuum-arc plasma generator with titanium or aluminum cathodes, which operated in a DC mode with the arc current 100 A, was mounted on the side flange of the vacuum chamber.

Two high-frequency short-pulse negative bias generators were used to carry out the investigations. The parameters of the first generator were: pulse duration 1–9 μs, pulse repetition rates 10^5 pulse per second (p.p.s.), negative pulse amplitude 0.5–3.5 kV. The parameters of a second generator were pulse duration 2.4 μs, pulse repetition rates 2.4×10^5 p.p.s., negative pulse amplitude 0.5–2 kV.

In these experiments, stainless steel and titanium substrates were used. The surfaces of the substrates were polished to $R_a = 0.035$ μm. The substrates were mounted on a massive holder. The distance from samples to the cathode of the vacuum arc evaporator was 38 cm.

The metal ion current density near the substrate surface was about 4.4 mA/cm^{-2}. Initially, the surface of each substrate was treated with ions using argon plasma and the high-frequency short-pulse bias [15]. Experiments with a tungsten grid were carried out to determine the effects of the "instantaneous" action and ion sputtering on the general dynamics of MPs number density decreasing. The tungsten grid, with a cell size 500 μm × 500 μm, with a transparency of 0.56 was placed at 0.8 cm from the substrate.

The MP densities on the substrate surface were studied using optical and electron (Hitachi TM–1000 and Hitachi TM–S 3400N) microscopes. Experimental data on changes found in MP number surface density are presented in the figures in absolute units and in the form of MP relative number surface density $k = N/N_0 = n/n_0$, where $N = n\,S$ – is the quantity of MPs located on the chosen area of substrate (S) at negative biasing; n = surface density of MP at negative biasing; $N_0 = n_0\,S$ = the quantity of MPs on the chosen area of a substrate at anode potential on the substrate surface ($\varphi_{sub} = 0$ V) at the chosen vacuum-arc plasma deposition time; n_0 = surface density of MPs at anode potential biasing on the substrate at a chosen time of metal plasma deposition; S – (chosen for the statistically reliable calculation of the MP quantity on the substrate surface. For each experimental point, total area for MP calculation made 60,000 μm^2.

Experimental results and discussion

Titanium vacuum arc plasma

For better understanding of what impact on the decrease of MPs surface density can be produced for MPs with different diameters, two substrates were treated for 1 min with $\varphi_b = 0$ V and $\varphi_b = -2$ kV and analyzed in detail using an electron microscope. The corresponding histograms of Ti MP number density distributions versus their sizes are shown in Fig. 1.

The data in Fig. 1 show that the impact of MPs with diameter smaller than 0.5 μm on the decreasing of MP number density was more substantial. Estimation shows that the surface density of small MPs was decreased almost fourfold. The number of MPs with sizes ranging from 0.5 μm to 1 μm was decreased by only 2.5-fold.

The number of MPs with diameter larger than 1.5 μm after the treatment time of 1 min did not change. The average relative surface density of MPs estimated from the data of histogram is 0.36.

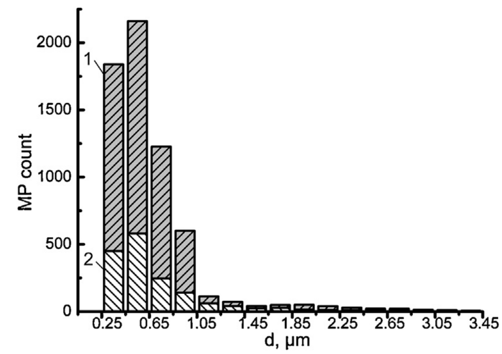

Fig. 1. Histogram of MP number density distribution versus MP diameter after 1 min of vacuum plasma deposition: 1 – substrate bias $\varphi_b = 0$ V; 2 – substrate at repetitively-pulsed negative bias with parameters: $\varphi_b = -2000$ V, $\tau = 7$ μs, $f = 10^5$ p.p.s.

Ion sputtering and repulsion of MPs

To determine the influence of the different physical mechanisms on the total dynamics of Ti MPs number surface density decreasing, four experiments with an additional tungsten grid placed at 0.8 cm from the substrate were carried out.

In the first case the grid had the anode potential. The substrate had negative high-frequency short-pulse biasing (Fig. 2a).

In the second experiment, on the contrary, the grid had the negative high-frequency short-pulse bias, but the substrate was under anode potential (Fig. 2b). It is necessary to mention that the use of a grid with cell sizes much smaller than the width of the sheath provides the opportunity to create an electric field near this electrode, which is almost the same as the field of a solid electrode. A non-uniform electric field in the case of a grid will occur at distances, only in some cell sizes. Thus, the negatively charged MP, entering from the plasma into a sheath, should be repelled in the same way as in the case with the solid electrode. Ion sputtering of the substrate and MPs should not take place in the second case, because after the acceleration of ions in the sheath before the grid, they will be decelerated in the electric field between the grid and the substrate.

In the third case, both the grid and the substrate had the same negative high-frequency short-pulse bias (Fig. 2c). When the grid and the sample are under negative bias, the strong electric field exists only before the grid. Between the biased grid and the substrate, the electric field is insignificant and defined by a space charge of ions in this gap. This means that in this case, there is a strong electric field near the grid for the electrostatic repulsion of charged MPs. At the same time, in this case ion sputtering of MPs should take place.

In the fourth experiment both the grid and the substrate had anode potential, and the usual deposition of metal plasma and MPs took place.

The results of all experiments are presented in Fig. 3. The dynamics of MP number surface density increasing with vacuum arc deposition time on substrate, when the grid and the substrate had anode potential, is shown in Fig. 3, curve 1.

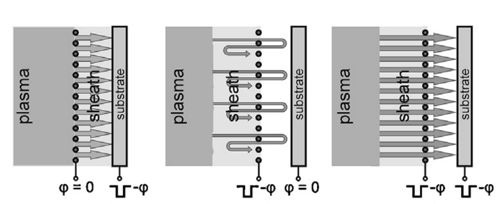

Fig. 2. Set of experiments with the additional grid electrode.

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