УДК 621.793

PLASMA STREAMS MIXING IN TWO-CHANNEL T-SHAPED MAGNETIC FILTER

D.S. Aksyonov, I.I. Aksenov, A.A. Luchaninov, E.N. Reshetnyak, V.E. Strel'nitskij
National Science Center "Kharkov Institute of Physics and Technology",
Kharkov, Ukraine
E-mail: strelnitskij@kipt.kharkov.ua

Ti-Al-N films were deposited by vacuum arc method. T-shaped magnetic filter with two channels was used for films preparation. Deposition was performed after aluminum and titanium separate plasma streams from two plasma sources were mixed into single one inside plasma duct having weakened magnetic field near its output. Obtained films have uniform distribution of composition and thickness on 180 mm diameter substrate surface. It was found that mixing and homogenization degree depends on nitrogen pressure, output magnetic field intensity and output-to-substrate distance. Film self-sputtering and aluminum preferential sputtering were observed for elevated negative substrate bias potentials.

INTRODUCTION

Nitride-based composite films, which have two and more components, possess enhanced (if compared to films with single component) mechanical properties, thermal stability and oxidation resistance. Such films can serve as protective ones in high-speed cutting machinery applications, especially if the use of cooling/lubricant liquids is not acceptable and environment is aggressive. Multicomponent films can be produced by vacuum arc technique using predefined content cathodes. Resulting films have nearly the same as cathode composition, but such cathodes are expensive and difficult-to-made. Besides, changing film composition requires cathode replacement, making it difficult to change film composition during deposition process and to search for new film compositions.

Said drawbacks can be avoided by use of several cathodes, made of different materials. Plasma streams generated from these cathodes should be mixed into single one before deposition occurs. Otherwise resulting films composition will not be homogeneous. Multiple-cathode systems might have one [1, 2] or multiple channel [3, 4] plasma ducts. In systems with one channel, different cathodes are arranged near each other [1, 2]. Plasma streams from each cathode move in common plasma duct in longitudinal magnetic field. Each stream is guided by its own group of magnetic lines of force. Therefore the streams either mixed slightly or not mixed al all. Systems with multiple channels usually have one cathode per channel. After passing through the channels, the streams travel inside common output section of the plasma duct with longitudinal magnetic field. Thereby resulting plasma is heterogeneous for the same reasons as for one channeled systems.

Plasma mixing and homogenization can be performed by use of additional devices, so-called homogenizers. Most of them are not well studied. Some are complicated, expensive and studied only in scope of homogenization capabilities (not mixing) [5, 6], some – do not provide sufficient mixing degree [3].

The objective of this work is to obtain experimental data on capabilities of two-channel T-shaped magnetic filter [7] to deposit composition-uniform Ti-Al-N films on large surfaces from mixed plasma streams.

EXPERIMENTAL DETAILS

Vacuum arc deposition system used for deposition was described in detail elsewhere [7] and schematically shown in Fig. 1. The system is equipped with two plasma sources 1 and 2 attached to T-shaped plasma duct 3 input sections P1 and P2 respectively. Each plasma source has anode A1/A2, cathode C1/C2, stabilizing coil S1/S2 and focusing coil (or anode coil) F11/F21 and F12/F22. Plasma duct 3 is attached to vacuum chamber 5 of "Bulat-6" apparatus via output section P3. Each plasma duct input section is equipped with deflecting coil D1/D2, and its output section has output coils L1 and L2. Substrate holder 4 located at distance z from the system output.

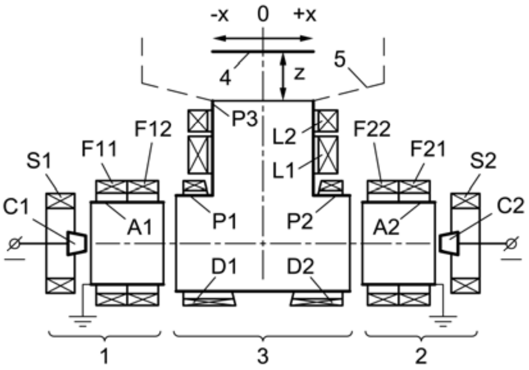


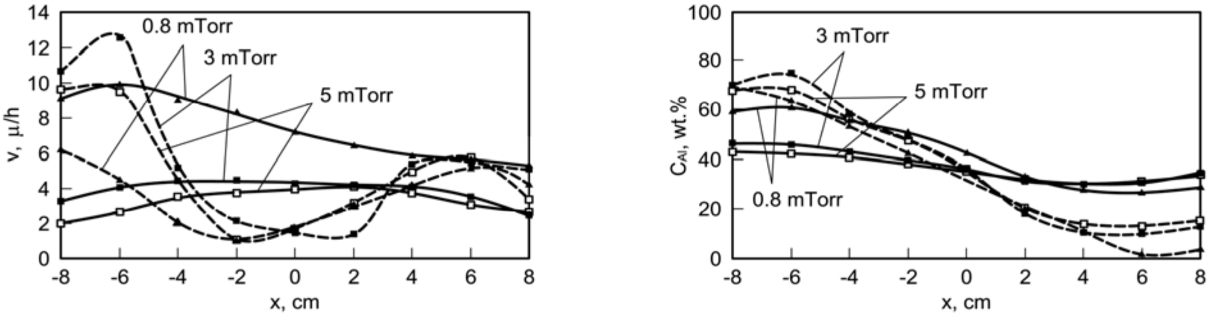
Fig. 1. Scheme of T-shaped magnetic filter equipped with two plasma sources

Aluminum was used as cathode C1 material, titanium – as cathode C2 material. Plasma sources arc currents were equal to 100 A in all experiments. Deposition was performed on polished molybdenum substrates with size 20×17×1 mm. Each experiment used nine such substrates arranged in one row (along x in Fig. 1) with 20 mm offset. Output-to-substrate distance z changed from 25 to 200 mm. Nitrogen pressure was sustained at constant level during deposition cycle and had values from 0.8 to 5 mTorr. Coil L2 current varied from − 3.8 to + 3 A. Other coils of the system had their current values fixed: $I_{S1} = I_{S2} = 1.5$ A, $I_{F11} = I_{F21} = -0.4$ A, $I_{L1} = 4$ A $I_{F21} = I_{F22} = 0.5$ A, $I_{D1} = I_{D2} = 0.5$ A. Negative coil current here and after means that the current in this

ВОПРОСЫ АТОМНОЙ НАУКИ И ТЕХНИКИ. 2011. №6.
Серия: Вакуум, чистые материалы, сверхпроводники (19), с. 116-120.

coil flows in opposite to another coils (with positive currents) sense.

Aluminum and titanium content were determined by X-ray fluorescent analysis using SPRUT spectrometer. Thickness of the films was measured with MII-4 optical interferometer. Eight measurements were made for each sample: four at the top and four at the bottom area of the sample. Obtained thickness data were averaged. Magnetic field plot calculations were made using "femm" software [8].



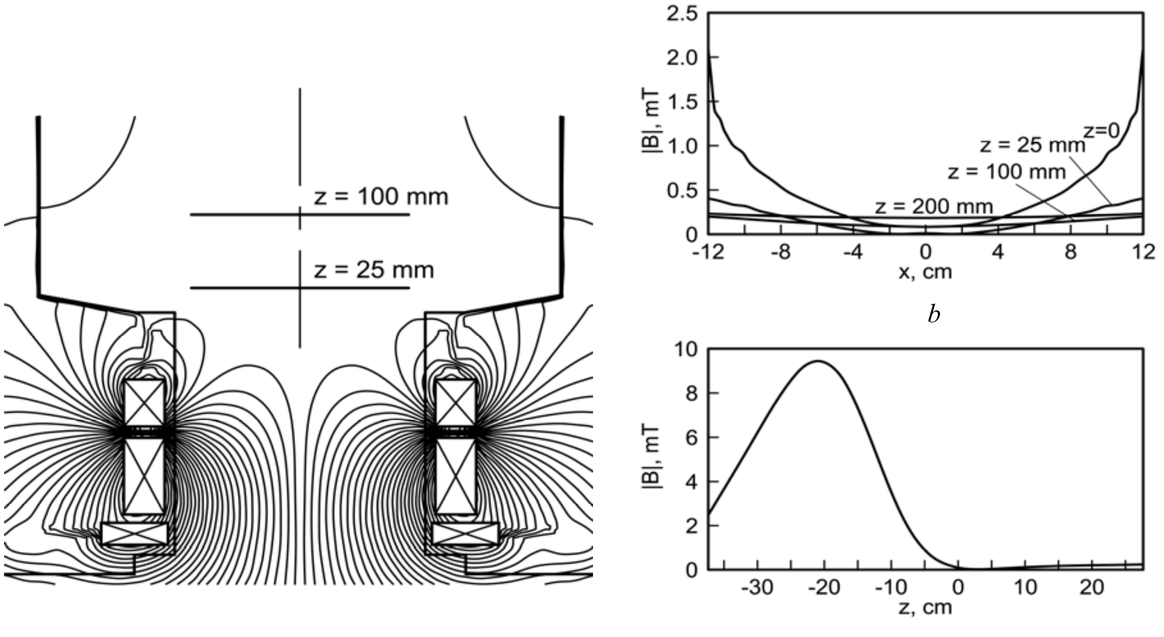
a *b*

Fig. 2. Radial distributions of film deposition rate (a) and aluminum content (b) for different nitrogen pressures. Solid lines – I_{L2} = − 3 A, dashed lines – I_{L2} = + 3 A. z = 25 mm, floating substrate bias

RESULTS AND DUSCUSSION

Magnetic field geometry (near the system output) and nitrogen pressure influence on film content and thickness (characterized by deposition rate) uniformity is shown in Fig. 2. While output coil L2 has positive current, deposited films are highly nonuniform since two plasma streams move parallel to each other in longitudinal magnetic field and almost no mixing occurs. Film thickness distribution has two peaks (see Fig. 2,a). Left peak corresponds to maximum aluminum content and right one – to titanium maximum content (minimum of aluminum content) which clearly confirmed by Fig. 2,b curves. Increase of nitrogen pressure in vacuum chamber lowers magnitude of the peaks due to higher plasma dissipation level on denser gas target. Opposite L2 coil current weakens magnetic field intensity at the system output and inside the vacuum chamber – magnetic field there is nearly absent (Fig. 3). Thus plasma loses its magnetization and tends to dissipate. It leads to increasing of plasma streams interdiffusion level and as a result – to higher mixing degree. Obtained films become much more uniform in thickness and composition.

As plasma mixing degree can be manipulated by controlling magnetic field intensity near the system output it is obvious to assume that content and thickness radial distributions can be confined by L2 coil current variation since it has great influence on the field intensity at the output. Fig. 4 shows how these distribution curves change their appearance with adjusting output magnetic field intensity. Changing L2 current from + 3 A (not shown on Fig. 4,a) to − 2 A value gradually lowers thickness peaks magnitude (approximately in 2−3 times for right and left peaks respectively) and increases thickness value at the system output axis (*x* = 0).



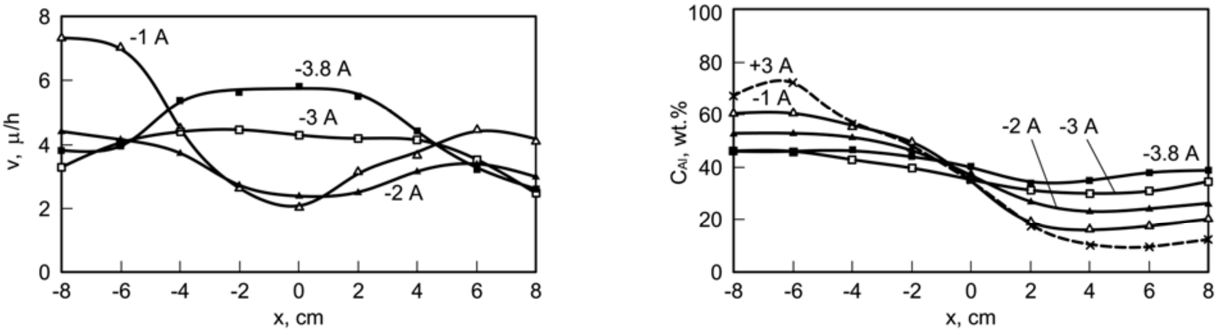
a *c*

Fig. 3. Magnetic field geometry at the system output (a), radial distributions of magnetic field induction (b) and magnetic field induction along the system output axis (c). I_{F12} = I_{F22} = 0.5 A

After further increase of L2 coil negative current from − 2 to − 3 A thickness peaks totally disappear and its distribution becomes most flat-shaped. It is evident that two plasma streams, which are separate before the weakened field area, become combined into single one after passing trough it, resulting in more uniform film growth. However, if L2 current increased further, the coil will produce cusp-shaped magnetic field with raised induction near the output opening of the duct and thus – to typical focusing of the combined plasma stream. Therefore, deposited film will have thickness peak at the system output axis (curve for $I_{L2} = -3.8$ A in Fig. 4,a). Aluminum content curves become more smoothed when L2 coil current changed from +3 to − 3.8 A.

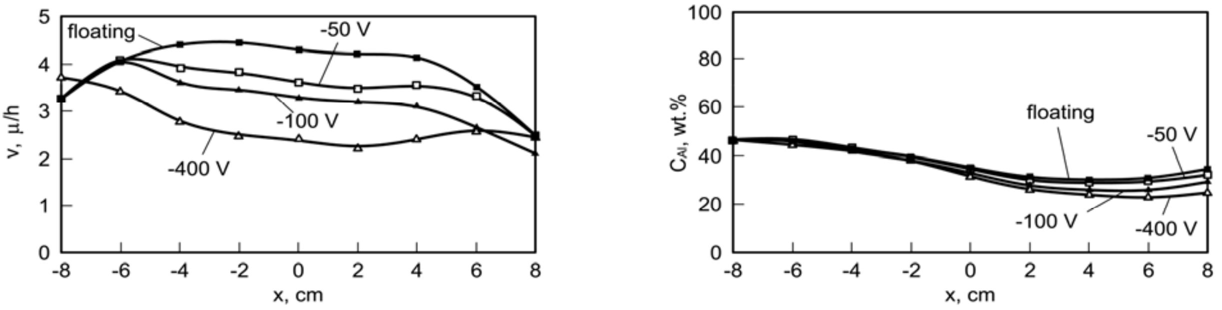
Analysis of the previous results [9] indicates that preferential sputtering of light elements from film can take place at certain substrate negative bias levels. It means that high negative bias can reduce aluminum content in films or can affect its composition uniformity. It can be assumed that aluminum preferential sputtering is caused by titanium ions bombardment and at lower negative substrate bias as compared to titanium self-sputtering one. So maximum yield should be where titanium ions flux is denser, i.e. closer to the plasma source with titanium cathode. This assumption is confirmed by Fig. 5 since left part of aluminum content curves remain unaffected up to − 400 V bias, while another part of said curves demonstrates aluminum losses resulting in content uniformity degradation. Aluminum content becomes lower with increasing negative bias. Deposition rate fall off is also observable in Fig. 5,a owing to self-sputtering effect.

All above presented experimental data were obtained while output-to-substrate distance *z* was equal to 25 mm. But most practical applications will require higher distance values. Data obtained for *z* value increased to 100 and 200 mm are shown in Fig. 6.



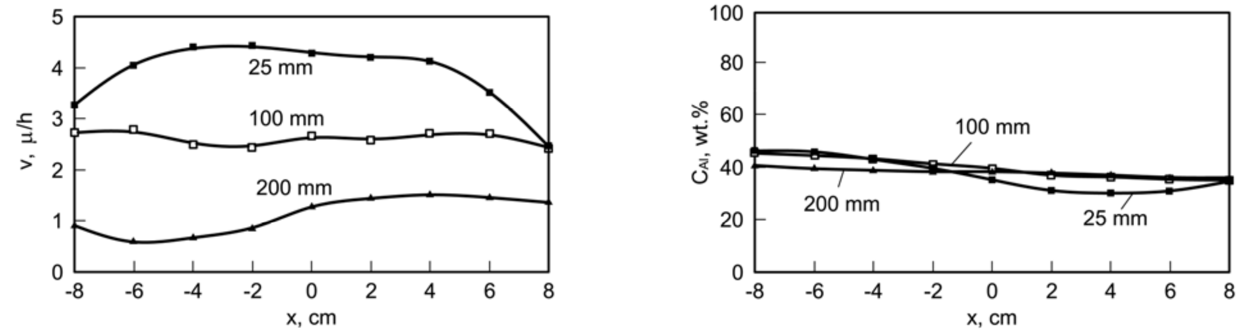
a *b*

Fig. 4. Radial distributions of film deposition rate (a) and aluminum content (b) for different currents in output coil L2 (I_{L2}). z = 25 mm, nitrogen pressure – 3 mTorr, floating substrate bias



a *b*

Fig. 5. Radial distributions of film deposition rate (a) and aluminum content (b) for different substrate biases. z = 25 mm, nitrogen pressure – 3 mTorr, $I_{L2} = -3$ A



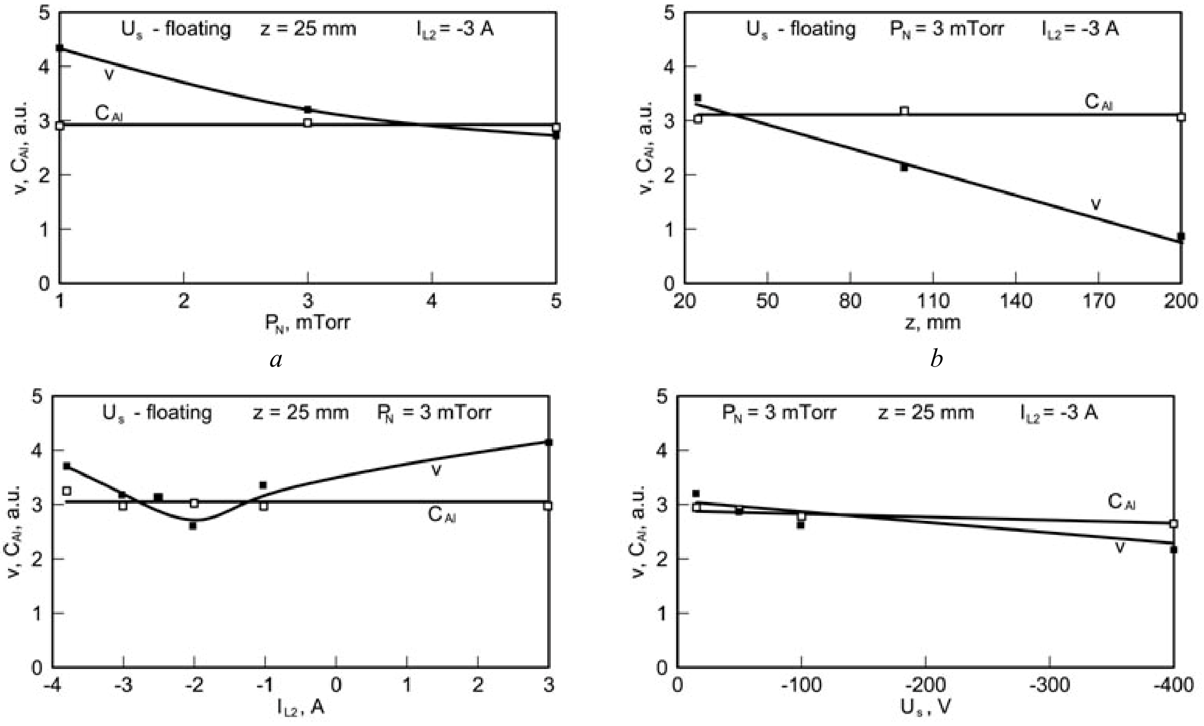
a *b*

Fig. 6. Radial distributions of film deposition rate (a) and aluminum content (b) for different distances between substrate and system output (z). Nitrogen pressure – 3 mTorr, floating substrate bias, $I_{L2} = -3$ A

It can be seen, that uniformity of film thickness and composition rises with the distance. Meanwhile a significant deposition rate lowering is also observed. Both of these factors can be explained by plasma stream dissipation in magnetic field with close to zero intensity: interdiffusion due to lack of magnetization provides mixing but elevated dissipation level leads to higher losses.

As it has been stated above, the investigated system allows mixing of two plasma streams from different materials into one stream. For additional confirmation of this fact, integral values of film aluminum content were calculated. For example, in case of aluminum radial distribution change due to one of the primary streams losses (losses of the streams are not equal) integral concentration change will be observed. In case of plasma streams mixing, regardless of the mixing degree, integral content value will not change.

It can be seen from the curves presented in Fig. 7 that integral aluminum content does not depend on nitrogen pressure, output-to-substrate distance and magnetic field intensity at the system output (in the investigated range of values). Integral aluminum content decreases slightly only at high (− 400 V) substrate bias. It is not a mixing-related effect, but aluminum preferential sputtering (see above). Based on integral value constancy one can conclude that change of aluminum content radial distributions shown in Fig. 2 and Fig. 4–6 is due to spatial redistribution of plasma components. That is, mixing of aluminum and titanium plasma streams onto single stream takes place. It should be noted, that constancy of integral film content makes it impossible to adjust film components concentration by controlling said deposition process parameters. And in the same time it allows to change any of them without the risk of unwanted film composition change. It is significant since change in such parameters like nitrogen pressure or substrate bias can be demanded to control, for example, films nitrogen content, their hardness, etc.



a *b* *c* *d*

Fig. 7. Dependence of integral film deposition rate and aluminum concentration on nitrogen pressure (a), output-to-substrate distance (b), output coil current (c) and substrate bias (d)

Investigated system capabilities to change deposited films composition are of interest. Film content can be varied by changing arc currents ratios in plasma sources or, presumably, by other deposition process parameter, not discussed in this paper. The study of such possibility requires additional experiments to be held. However, this objective is beyond the scope of this work and will be investigated in subsequent studies after appropriate experiments.

CONCLUSION

It was shown, that vacuum arc produced Ti-Al-N films can be obtained by deposition of separate Al and Ti plasma streams after they were mixed into single stream using two-channel T-shaped magnetic filter with two pure-metal cathodes. Mixing of separate plasma streams is achieved when they pass through weakened magnetic field area near T-shaped plasma duct output. Resulting films have uniform composition and thickness on a 180 mm diameter sized surface. Mean aluminum content value is 40 wt.%, and deviation does not exceed 3 wt.% level.

It was found that integral film content is not affected by nitrogen pressure, magnetic field intensity at the system output and output-to-substrate distance (in the studied values range). Their change results in spatial redistribution of film components.

Good uniformity of film content and thickness along with relatively high deposition rate (as for 180 mm diameter substrates) make investigated system applicable to practical use.

REFERENCES

1. R. Ben-Ami, V.N. Zhitomirsky, R.L. Boxman, S. Goldsmith. Plasma distribution in a triple-cathode vacuum arc deposition apparatus // *Plasma Sources Sci. Technol.* 1999, v. 8, p. 355 − 362.
2. A. Anders, N. Pasaja, S. Sansongsiri. Filtered cathodic arc deposition with ion-species-selective bias // *Rev. Sci. Instrum.* 2007, v. 78, p. 063901 − 5.
3. T. Mashiki, H. Hikosaka, H. Tanoue, H. Takikawa, et al. TiAlN film preparation by Y-shape filtered-arc-deposition system // *Thin Solid Films*. 2008, v. 516, p. 6650 − 6654.
4. H. Dai, Y. Shen, J. Wang, M. Xu. Fabrication for multilayered composite thin films by dual-channel vacuum arc deposition // *Rev. Sci. Instrum.* 2008, v. 79, p.065104 − 5.
5. S. Anders, S. Raoux, K. Krishnan, R.A. MacGill, I.G. Brown. Plasma distribution of cathodic arc deposition systems. // *J. Appl. Phys.* 1996, v.79 (9), p. 6785 − 6790.
6. M.M.M. Bilek, A. Anders, I.G. Brown. Magnetic system for producing uniform coatings using a filtered cathodic arc // *Plasma Sources Sci. Technol.* 2001, v. 10, p. 606 − 613.
7. I.I. Aksenov, D.S. Aksyonov, V.V. Vasilyev, A.A. Luchaninov, E.N. Reshetnyak, V.E. Strel'nitskij. Two-Cathode Filtered Vacuum Arc Plasma Source. // *IEEE Trans. Plasma Sci.* 2009, v. 37, iss. 8, p. 1511 − 1516.
8. D.C. Meeker, Finite Element Method Magnetics, Version 4.0.1, http://femm.foster-miller.net.
9. D.S. Aksyonov, I.I. Aksenov, A.A. Luchaninov, E.N. Reshetnyak, V.E. Strel'nitskij. Synthesis of Ti-Si and Ti-Si-N Coatings by Condensation of Filtered Vacuum-Arc Plasma // *Problems of Atomic Science and Technology. Series "Vacuum, Pure Materials, Superconductors".* 2009, N6, p.2 68 − 272.

Статья поступила в редакцию 18.04.2011 г.

СМЕШЕНИЕ ПОТОКОВ ПЛАЗМЫ В ДВУХКАНАЛЬНОМ Т-ОБРАЗНОМ МАГНИТНОМ ФИЛЬТРЕ

Д.С. Аксёнов, И.И. Аксёнов, А.А. Лучанинов, Е.Н. Решетняк, В.Е. Стрельницкий

Осаждение Ti-Al-N-покрытий производилось вакуумно-дуговым методом с использованием двухканального Т-образного магнитного фильтра. Потоки алюминиевой и титановой плазмы смешивались в один поток. Смешивание потоков производилось внутри выходной секции плазмовода в области ослабленного магнитного поля. Покрытия, полученные осаждением смешанного плазменного потока, однородны по составу и толщине на подложке диаметром 180 мм. Установлено, что степень смешивания и гомогенизации зависит от давления азота в рабочем объёме, напряжённости магнитного поля вблизи выходной секции плазмовода и расстояния между подложкой и выходным сечением плазмовода. При повышенном отрицательном потенциале подложки наблюдались самораспыление осаждаемого покрытия и преимущественное распыление алюминия из покрытия.

ЗМІШУВАННЯ ПОТОКІВ ПЛАЗМИ В ДВОКАНАЛЬНОМУ Т-ПОДІБНОМУ МАГНІТНОМУ ФІЛЬТРІ

Д.С. Аксьонов, І.І. Аксьонов, О.А. Лучанінов, О.М. Решетняк, В.Є. Стрельницький

Осадження Ti-Al-N-покриттів проводилось вакуумно-дуговим методом із застосуванням двоканального Т-подібного магнітного фільтра. Потоки алюмінієвої та титанової плазми змішувались в один потік, після чого проводилось осадження цього результуючого потоку. Змішування потоків відбувалося всередині вихідної секції плазмоводу в області послабленого магнітного поля. Отримані покриття однорідні за складом та товщиною на підкладці діаметром 180 мм. Встановлено, що ступінь змішування та гомогенізації залежнім від тиску азоту в робочому об'ємі, напруженості магнітного поля поблизу вихідної секції плазмоводу та відстані між підкладкою та виходом плазмоводу. При підвищеному негативному потенціалі підкладки спостерігалося саморозпилення покриття та переважне розпилення алюмінію із покриття.