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ABSTRACT
Herein, we investigate the influence of powder metallurgical manufactured \( \text{Ti}_0.5\text{Al}_0.5 \) cathode grain size (45-150 \( \mu \)m) on the properties of a DC arc discharge, for \( \text{N}_2 \) pressures in the range 10\(^{-5} \) Torr (base pressure) up to 3x10\(^{-2} \) Torr. Intermetallic TiAl cathodes are also studied. The arc plasma is characterized with respect to ion composition, ion charge state, and ion energy, and is found to change with pressure, independent on choice of cathode. Scanning electron microscopy, X-ray diffraction, and Energy-dispersive X-ray spectroscopy of the cathode surfaces and the concurrently deposited films are used for exploring the correlation between cathode-, plasma-, and film composition. The plasma has a dominating Al ion content at elevated pressures, while the film composition is consistent with the cathode composition, independent on cathode grain size. Cross-sections of the used cathodes are studied, and presence of a converted layer, up to 10 \( \mu \)m, is shown, with an improved intermixing of the elements on the cathode surface. This layer is primarily explained by condensation of cathode material from the melting and splashes accompanying the arc spot movement, as well as generated plasma ions being redeposited upon returning to the cathode. The overall lack of dependence on grain size is likely due to similar physical properties of Ti, Al and TiAl grains, as well as the formation of a converted layer. The presented findings are of importance for large scale manufacturing and usage of Ti-Al cathodes in industrial processes.

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I. INTRODUCTION

Arc evaporated (Ti,Al)N thin films are widely used as hard and wear-resistant coatings due to their superior mechanical properties and oxidation resistance.\(^1\)\(^-\)\(^4\) Industrial PVD synthesis of (Ti,Al)N by DC arc with plasma generation from a Ti-Al compound cathode in a nitrogen atmosphere is an established technique.\(^5\)\(^-\)\(^7\) Extensive studies have been carried out on the effect of the properties of the arc generated material flux on the resulting coatings, including the influence of cathode composition, nitrogen pressure, electrical potential (bias) and temperature of the substrate.\(^8\)\(^-\)\(^15\) However, to date, little is known about the influence of microscale properties and grain size of Ti-Al cathodes on the plasma generation process and subsequent film formation.

With a particular focus on a compound cathodes used in the arc deposition process, input parameters such as phase composition, arc current, applied magnetic field, and operation temperature, are acknowledged to have significant impact on the arc behavior, generated plasma characteristics, and coating properties, see e.g. Refs. 16–20 and 15. Recently, it was shown that movement of the cathode spot, film deposition rate, film density and defect morphology and film composition can be influenced by the microstructure of the used cathode.\(^21\)\(^,\)\(^22\) Movement of the arc spot on the surface of a compound cathode, where areas composed of different phases may exist, can obviously lead to a change in discharge properties. A local variation of the work function, the melting temperature, and electrical and thermal conductivity, have a strong influence on the arcing process, exemplified by, e.g., a change in macroparticle
TABLE I. Manufacturing details of the used cathodes.

| Cathode | Ti powder | Al powder | Manufacturing | Manufacturing temperature, °C |
|---------|-----------|-----------|---------------|-------------------------------|
| ST (Standard) | < 160 µm | < 125 µm | Forging of elemental powders | 350 |
| FK | < 45 µm | < 63 µm | Forging of elemental powders | 350 |
| FK-IM | < 45 µm | < 63 µm | Hot isostatic pressing of elemental powders | 750 |
| IM | Intermetallic TiAl powder | < 160 µm | Spark Plasma Sintering of intermetallic powders | 1300, SPS |

II. EXPERIMENTAL DETAILS

A. Characterization of the as-received cathodes

The experiments were performed using a deposition system equipped with an industrial scale DC arc source (Ionbond) for 63 mm diameter cathodes. No magnetic field within the source was used. Three Ti$_{0.50}$Al$_{0.50}$ (at. %) cathodes, produced by powder metallurgy, and with different grain size, were investigated. Manufactory details of the cathode are presented in Table I. As shown in the energy dispersive X-ray spectroscopy (EDX) maps of Figure 1, the grain size decreases going from ST to FK and to FK-IM. The IM cathode is a completely intermetallic Ti$_{0.50}$Al$_{0.50}$ (at. %) cathode created through spark plasma sintering of intermetallic TiAl powder. Figure 1 shows that the as-received IM cathode displays an Al-rich layer on its surface. This is likely caused by the cathode production process and smearing of Al upon cutting. The thickness of the layer does not exceed 1 µm and is removed in first minutes of operation.

Figure 2 demonstrates the x-ray diffractometry (XRD) patterns of the as-received cathodes. The patterns show that the signals from pure Ti and Al are the most pronounced for the ST cathode, while the signals of the pure elements for the intermetallic cathode are very low. The results also show that the hot isostatic pressing of elemental Ti and Al powders performed for the FK-IM cathode at 750°C seems to result in creation of a cathode bulk material having comparable phase composition with the IM cathode, i.e. the FK-IM cathode seems to be an intermetallic one as well. Notably, in the patterns for the IM cathode, footprints of the Al-rich layer seen in Fig. 1 are not detectible; this can be caused by a difference in the penetration depths of XRD and EDX techniques.
B. Plasma analysis

The cathodes were used for at least 10 minutes prior to any measurements, to remove eventual surface contaminants and achieve steady state conditions. In all here performed experiments, the arc source was operated at 90 A arc current. The base pressure of the system was $5 \times 10^{-5}$ Torr. A mass-energy-analyzer (MEA, Hiden Analytics model EQP) was placed in front of the arc source with the orifice (50 µm diameter) about 35 cm from the cathode surface. For each cathode, the plasma was characterized through mass-scans at fixed ion energy and energy-scans at fixed mass-to-charge ratio for all detected ions. The energy scans were recorded in steps of 0.25 eV/charge up to 200 eV/charge to capture the entire ion energy distribution (IED). Presence of isotopes in the ion flux and their influence on the relative ratios of the measured IEDs were evaluated according to previous work. Each IED was recorded at least three times to ensure consistency of the data. Over time the MEA orifice may be coated and the recorded intensity reduced as an effect of

![Graph of XRD patterns from the as-received Ti-Al cathodes.](image)

![Graph of IEDs of Ti (left) and Al (right) ions measured at base pressure ($5 \times 10^{-5}$ Torr) from the cathodes a) ST, b) FK, c) FK-IM and d) IM.](image)
reduced orifice size. To prevent such effect, the inlet analyzer channel was cleaned after finalized analysis from every cathode. To determine the plasma ion charge states and the total plasma composition, the IEDs were treated in line with Refs. 30 and 11.

C. Film growth

Films were deposited by fixing a Si (100) substrate in a position equivalent to the front end of the plasma analyzer, at grounded potential. The deposition time is 10 min for a film. The temperature calibration showed a substrate temperature not exceeding 250 °C during plasma generation, and no external heating was supplied.

D. Structural and compositional materials analysis

The phase structures of the cathodes and films were examined by x-ray diffractometry using a PANalytical X’PERT X-ray diffractometer with a line-focus Cu Kα X-ray source, where θ-2θ scans were recorded in the 2θ-range from 25° to 140°. Compositions of films and cathodes were characterized using a LEO 1550 scanning electron microscope (SEM) equipped with energy dispersive X-ray spectroscopy.

III. EXPERIMENTAL RESULTS

A. Plasma characterization

Ti and Al ions of charge states 1+, 2+, and 3+ were detected in the plasma from all Ti-Al cathodes. Fig. 3 exemplifies the measured ion energy distributions. No significant intensity was recorded for charge states of 4+ and higher.

First to be noted in Fig. 3 is the similarity of the IEDs for plasmas generated from the different cathodes. The IEDs were integrated to allow evaluation of the average ion energy and the average ion charge state, as well as an estimate of the ion plasma composition, see Figure 4 and the variation in plasma properties over the pressure range 5x10⁻⁵ Torr – 5x10⁻³ Torr of N₂.

The influence of N₂ pressure on the average ion charge state, the average ion energy and the composition of plasmas generated from the Ti-Al cathodes has previously been considered in Ref. 12. The present study, however, is focused on the influence of the cathode grain size on the aforementioned properties. Altogether, Fig. 4 shows that all points measured for the different cathodes are in a range with deviations below ±10%. This is close to an estimated reproducibility of the results of ±5%. It can therefore be concluded that the cathode grain size has no significant effect on the plasma generation.

B. Thin film characterization

To investigate the effect of the cathode grain size on the intensity of macroparticle generation, the film deposition rate and the resulting film elemental ratio, thin films were grown at base pressure and at 5x10⁻³ Torr of N₂ for 10 min, see the film surfaces in Fig. 5.

In line with the plasma characterization, Figs. 3 demonstrates no significant effect of the grain size on the Al/Ti ratio, the intensity...
of the macroparticle generation and the deposition rate. The reduction in macroparticle generation and deposition rate with increasing pressure has been shown elsewhere.\textsuperscript{11,31}

Even though using a low deposition temperature and, therefore, a possible lack of an informing enough phase picture, XRD diagnostics of the films was performed, see Fig. 6.

The XRD data of the films demonstrates a very close match of the patterns from the films deposited from the cathodes with different grain size. The peak at $2\theta = 33^\circ$ can not be unambiguously identified. Due to the low crystallinity of the films, the XRD data from the different films were compared, but not interpreted and discussed in detail.

C. Characterization of the used cathodes

For the as-received cathodes, the elements are unevenly distributed, as shown in Fig. 1. On the contrary, a homogeneous distribution of the elements is found for the used Ti-Al cathodes, see the top two rows in Fig. 7. This similarity between the operation surfaces of the used cathodes is also demonstrated by the SEM images in the bottom row of Fig. 7.

An effect of different grain size on the formation of intermetallic compounds on the cathode surface is studied by XRD diagnostics, see Figure 8. The XRD patterns measured for the different cathodes are found to be similar, both for plasma generation at base pressure and for plasma generation in the presence of $N_2$, see Fig. 8. In line with the analysis of the deposited films, the XRD data for the cathodes is mainly used for identifying potential differences between the cathodes.

This is motivated by the different Ti, Al, Ti-Al and their nitrides having high intensity peaks at almost the same positions, making attempts of detailed evaluation of phases at the cathode surface challenging. It should also be noted that the penetration depth of the X-rays could be higher than the thickness of a converted surface layer, i.e. the initial bulk material structures of the cathodes could also be seen. Efforts to clarify phase structures existing at a
The empirical cohesive energy rule establishes a correlation between the cohesive energy of the cathode material and the properties of the generated plasma.\textsuperscript{27} For Ti-Al intermetallic compounds, the rule suggests that arcing from a surface consisting of areas of single elements and areas of intermetallic compounds may result in only slightly different plasma properties. The range of cohesive energies of Ti, Al and their intermetallics is between the cohesive energies of Ti and Al, i.e., in a range of \(\sim 1.5\) eV.\textsuperscript{11,12} Furthermore, the work function of the elements are also similar (Ti \(- 4.33\) eV, Al \(- 4.06\) eV). This suggests that changes in plasma generation during movement of the spot from one grain to another is minor.\textsuperscript{27}

The cathode used at base pressure and in a reactive N\(_2\) atmosphere have previously been performed and is presented in previous works.\textsuperscript{11,12,13} Still, the here presented similarity of the XRD results, combined with the other experimental data, suggests that the initial state of the cathode is of less importance, as the plasma generation change the cathode operational surface. The reduction in intensity at low diffraction angles for the used cathodes is caused by shadowing of the cathode operating surface by the cathode outer walls forming during the arcing process.

\textbf{IV. DISCUSSION}

The principal objective of this work is to study the possible influence of cathode grain size and/or presence of cathode intermetallic compounds, on the thin film deposition process using Ti–Al cathodes produced by powder metallurgy. Including three cathodes based on intermixing of elemental Ti and Al powders, where the used manufactory processes resulted in creation of one completely intermetallic cathode, and a reference cathode build on intermetallic Ti-Al powder, all examined parameters show close to no dependence on the studied properties.

The empirical cohesive energy rule establishes a correlation between the cohesive energy of the cathode material and the properties of the generated plasma.\textsuperscript{27} The similar structural and compositional evolution of the cathode surface during plasma generation on the cathodes can be explained by the thermal energy generated by the arc spot, in turn resulting in local temperatures \(>10\) 000 K. This greatly surpasses the boiling point of both elements (Ti \(- 3560\) K and Al \(- 2743\) K). Due to the movement of the arc spot, the cathode surface undergoes cycles of evaporation, melting and solidification. The evaporation and melting processes destroy any initial phase structure while the solidification creates a new one. The latter is determined by the Ti/Al ratio and solidification conditions such as temperature gradient, cooling rate, etc. The XRD presented in Figure 6 indicates that those conditions are similar for the here studied cathodes.

Another mechanism which may be relevant is splashing of cathode material from the active area of the arc spot. The explosive nature of the plasma generation within the arc spot creates a pressure in the GPa-range, right in front of the molten pool of the cathode active area.\textsuperscript{34–36} This splashed material from the pool results in formation of overlapping craters and, consequently, may at least in part be responsible for elemental mixing of material at the cathode surface during operation. It should also be noted that a vast part of the generated ions returns to the cathode and condensate on the cathode surface,\textsuperscript{27} which also influence the surface phase structure and composition.

The above considered processes accompanying the evolution of the cathode surface during arcing is described for the metallic mode of the arc discharge (arc type 2) in vacuum. However, the observations and the discussion are still generally true also for the reactive mode (arc type 1) in a reactive atmosphere. In the reactive mode, when the arc discharge typically has several simultaneously operating spots, the current and, therefore, the power per spot is lower compared to the metallic mode.\textsuperscript{11,12,13} Still, there are continuous cycles of melting-evaporation-solidification of local areas of the cathode, splashed cathode material from active areas and condensation of plasma ions returning to the cathode surface. The melting temperatures of nitrides are generally higher than for its elemental constituents. As a result, a change in volume of the molten pool of the active surface area of the cathode can be expected. However, comparing the melting temperatures of the pure elements (Ti \(- 1941\) K and Al \(- 933\) K) and the nitrides (for Ti \(- 3203\) K and Al \(- 2473\) K) with the temperature within the arc spot (up to several thousand degrees), one can expect that even for arc type 1 mode of operation, a notable amount of the cathode material within the active area of the spot is melted and the initial phase structure destroyed. Moreover, the arc spot can be of type 2 even in a reactive atmosphere, typically switching between the modes.\textsuperscript{11,12,13}

In Ref. 21, effects of the cathode grain size on primarily macroparticle generation have been found for Ti–Si cathodes. Furthermore, a converted layer of a thickness up to 5 \(\mu\)m has been detected for a Ti–Si cathode with a grain size of 600 \(\mu\)m used in N\(_2\).
atmosphere. Fig. 1 shows that in the present work, the maximum grain size of the Ti-Al cathodes is comparable to the Ti-Si cathode in previous work. To quantify the converted layer thickness for the here studied cathodes, cross-sections of the ST and IM cathodes were studied by SEM-EDX. For the IM cathode, no change in element distribution was detected when comparing the section close to the operational surface with the material in the cathode body. This is opposed to the EDX map of the operational surface of the ST cathode, shown in Fig. 9, which shows presence of a converted layer composed of more homogeneously distributed elements.

It is seen in Fig. 9, that the thickness of the layer is significantly smaller than the grain size, and typically in the range of up to 10 µm. This is consistent with the layer originating from splashing of the cathode material from the liquid bath within the arc spot, as well as re-condensation of cathode elements from the generated plasma. Considering that the converted layer is present over the whole cathode surface, the melting/splashing processes associated with the arc spot formation may be of less importance for the layer formation, in particular within a one-element grain in a location not close to the grain boundaries (a spot glowing on a Ti grain, far from the grain border, will not cause any converted layer with Ti-Al inter-mixing due to splashing). The arc spot is generally accepted to have a size within a range of a few µm. Therefore, one can assume that a smaller layer thickness leads to more exposure of the original grains to the active spot and, therefore, a stronger influence on individual grains on the discharge process. That is, for a large enough grain size, i.e. significantly larger than the arc spot. Since there is larger discrepancies between the properties of plasma originating from Ti and different Ti-Si phases, compared to between Ti, Al and Ti-Al phases, this can lead to more pronounced changes in the glowing conditions with the exposure of different Ti-Si phases to the spot. It results in the perceptible influence of grain size on arcing from a Ti-Si cathode detected in Ref. 21. In the present work, for the Ti-Al cathodes, such influence seems to be too small to be clearly detected. In Ref. 15, a slightly preferred erosion of the Al content in the cathodes and a weak dependence of the macroparticle intensity on the cathode grain size were suggested, and in turn explained by the difference in the working functions and the cohesive energies of Al and Ti. However, as mentioned above, these characteristic parameters are quite similar for Ti and Al, and, for the here studied DC arcing process, experimental results do not show such correlation.

The arc operation influences the surface conditions in several ways. For instance, the thickness of a converted layer may be determined, in analogy of the cathode contamination process,
by the erosion rate of the cathode, and by how often the arc spot repeats its track. If the arc spot frequently runs circularly in the outer area of the cathode, which is typically the case in the presence of a permanent magnet in DC arc sources (not used here), the thickness of a converted layer due to condensation of returning cathode material would be higher at the center of the cathode. The erosion rate, which on one side determines how much of the surface layer is destroyed and from the other side the density of the generated plasma, depends on the cathode material, its reactivity, and the presence and pressure of a reactive gas. Altogether, the cathode surface can be expected to be nonhomogeneous. However, since the major part of all generated ions is going from the plasma back to the cathode surface, formation of a converted layer with an improved intermixing of the cathode elements is expected to occur at the whole surface, for all cathodes, despite their elemental composition and grain sizes. To what extent that influence the plasma generation, likely depends on the thickness of the layer in combination with the properties/inhomogeneity of the underlying material.

V. CONCLUSION

Vacuum arc plasma from Ti$_{0.5}$Al$_{0.5}$ compound cathodes with different grain sizes has been characterized with respect to ion composition, ion charge state, and ion energy in vacuum and reactive N$_2$ atmosphere. Concurrent deposition of thin films has been done for evaluation of primarily macroparticle generation and film composition. A change in phase structures and compositions of operational surfaces of the cathodes after the arcing process has been studied. In the studied N$_2$ pressure range, no influence of the grain size on the properties of the generated plasma and the deposited films was detected, likely due to similar cohesive energies of the elements and their intermetallic compounds. Still, a converted layer up to 10 µm was found at the cathode surface, with an improved intermixing of the elements, possibly also contributing to the lack of dependence of cathode grain size on the arcing process. The origin of this layer is assumed to be formed from condensation of returning cathode material (ions) from the generated plasma, and repeated melting and solidification processes accompanying movement of the arc spot and a high plasma pressure within that spot leading to splashing of the cathode material from the active area. At the operational surface of the cathodes herein, the formed layer thickness, phase structure and elemental composition was found independent on the cathode grain size. The presented findings are of importance for large scale manufacturing and usage of Ti-Al cathodes, and contributing towards fundamental understanding of a DC arc discharge from compound cathodes.

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REFERENCES

1. D. McIntyre, J. Greene, G. Hakansson, E. Sundgren, and W. Münz, J. Appl. Phys. 67(3), 1542–1553 (1990).
2. C. Jarm, H. Stock, and P. Mayr, Surf. Coat. Technol. 108-109, 206–210 (1998).
3. W. Münz, J. Vac. Sci. Technol. A 4(6), 2717 (1986).
M. Odén, “Influence of Ti–Si cathode grain size on the cathodic arc process and a magnetic field,” J. Appl. Phys. 113, 103305 (2013).

A. Hörling, L. Hultman, M. Odén, J. Sjölén, and L. Karlsson, “Thermal stability of arc evaporated high aluminum-content Ti$_x$-…Al$_3$N thin films,” J. Vac. Sci. Technol. 20, 1815 (2002).

M. M. M. Bilek, P. J. Martin, and D. R. McKenzie, J. Appl. Phys. 83(6) (1998).

M. Li and F. Wang, Surf. Coat. Technol. 167, 197–202 (2003).

Y. Chang, D. Wang, and C. Hung, Surf. Coat. Technol. 200, 1702–1708 (2005).

I. Zhirkov, A. Eriksson, A. Petruhins, M. Dahlqvist, A. Ingason, and J. Rosen, “Effect of Ti-Al cathode composition on plasma generation and plasma transport in direct current vacuum arc,” J. Appl. Phys. 115, 123301 (2014).

I. Zhirkov, E. Öks, and J. Rosen, “Effect of N$_2$ and Ar gas on DC arc plasma generation and film composition from Ti-Al compound cathodes,” Journal of Applied Physics 117(21), 213301 (2015).

F. Aliaj, N. Syla, S. Avdijaj, and T. Dilo, “Effect of bias voltage on microstructure and mechanical properties of arc evaporated (Ti, Al)N hard coatings,” Bull. Mater. Sci. 36(3), 429–435 (2013).

D. Rafaja, C. Polzer, G. Schreiber, P. Polcik, and M. Kathrein, “Surface modification of Ti–Al targets during cathodic arc evaporation,” Surf. and Coatings Technology 205(21-22), 5116–5123 (2011).

B. Syed, J. Zhu, P. Polcik, S. Kolozsvári, G. Hakansson, L. Johnson, M. Ahlgren, M. Joesaar, and M. Odén, ”Morphology and microstructure evolution of Ti-50 at.% Al cathodes during cathodic arc deposition of Ti-Al-N coatings,” Journal of Applied Physics 121, 245309 (2017).

I. Zhirkov, A. O. Eriksson, and J. Rosen, ”Ion velocities in direct current arc plasma generated from compound cathodes,” J. Appl. Phys. 114, 213302 (2013).

K. P. Savkin, Yu. G. Yushkov, A. G. Nikolaev, E. M. Oks, and G. Yu. Yushkov, Rev Sci Instrum 81(2), 02A501 (2010).

A. O. Eriksson, I. Zhirkov, M. Dahlqvist, J. Jensen, L. Hultman, and J. Rosén, “Characterization of plasma chemistry and ion energy in cathodic arc plasma from Ti–Si cathodes of different composition,” Journal of Applied Physics 113(16), 163304 (2013).

I. J. Sasaki and I. Brown, Journal of Applied Physics 66, 5198–5203 (1989).

J. Rosén, A. Anders, S. Mráz, and J. Schneider, “Charge-state-resolved ion energy distributions of aluminum vacuum arcs in the absence and presence of a magnetic field,” J. Appl. Phys. 97, 103306 (2005).

J. Zhu, M. Jõesaar, P. Polcik, J. Jensen, G. Greczynski, L. Hultman, and M. Odén, “Influence of Ti–Si cathode grain size on the cathodic arc process and resulting Ti–Si–N coatings,” Surface and Coatings Technology 235(25), 637–647 (2013).

J. Zhu, A. Eriksson, N. Ghafoor, M. P. Johansson, J. Sjölén, L. Hultman, J. Rosén, and M. Odén, “Characterization of worn Ti–Si cathodes used for reactive cathodic arc evaporation,” Journal of Vacuum Science & Technology A: Vacuum, Surfaces, and Films 28, 347–353 (2010).

I. Zhirkov, A. Petruhins, P. Polcik, S. Kolozsvári, and J. Rosen, “Generation of super-size macroparticles in a direct current vacuum arc discharge from a Mo-Cu cathode,” Applied Physics Letters 108(5), 054103 (2016).

I. Zhirkov, P. Polcik, S. Kolozsvári, and J. Rosen, “Macroparticle generation in DC arc discharge from a WC cathode,” Journal of Applied Physics 121, 103305 (2017).

I. Zhirkov, L. Landålv, E. Göthelid, M. Ahlgren, P. Eklund, and J. Rosen, ”Effect of Si on DC arc plasma generation from Al-Cr and Al-Cr-Si cathodes used in oxygen,” Journal of Applied Physics 121(8), 083303 (2017).

T. Usumi, ”Measurements of cathode spot temperature in vacuum arcs,” Appl. Phys. Lett. 18, 218 (1971).

A. Anders, Cathodic Arcs. From Fractal Spots to Energetic Condensation, 1 ed. (Springer, New York, 2008).

G. Korb, ”Process for the manufacture of a target for cathodic sputtering,” Patent US 4752335, 1987.

P. Wilhartitz, S. Schönauer, and P. Polcik, ”Method for producing an evaporation source,” Patent EP1335995, 2003.

I. Zhirkov, E. Öks, and J. Rosen, ”Experimentally established correlation between ion charge state distributions and kinetic ion energy distributions in a direct current vacuum arc discharge,” Journal of Applied Physics 117(9), 093301 (2015).

I. Zhirkov, A. Petruhins, and J. Rosen, ”Effect of cathode composition and nitrogen pressure on macroparticle generation and type of arc discharge in a DC arc source with Ti–Al compound cathodes,” Surface & Coatings Technology 281, 20–26 (2015).

I. Zhirkov, A. Petruhins, and J. Rosen, ”Effect of cathode composition and nitrogen pressure on macroparticle generation and type of arc discharge in a DC arc source with Ti–Al compound cathodes,” Surface & Coatings Technology 281, 20–26 (2015).

G. Mesyats, Ectons in vacuum discharge (Nauka, Moscow, 2000).

S. Anders and B. Juttner, ”Influence of residual gases on cathode spot behavior,” IEEE Transactions on Plasma Science 19(5), 705–712 (1991).

K. Jakubka and B. Juttner, “On the influence of surface conditions on initiation and spot types of unipolar arcs in a Tokamak,” Journal of Nuclear Materials 102, 259–266 (1981).

M. Kühn and F. Richter, ”Characteristics in reactive arc evaporation,” Surface and Coatings Technology 89(1-2), 16–23 (1997).