ELSEVIER

Surface and Coatings Technology 146–147 (2001) 195–200

SURFACE & COATINGS TECHNOLOGY

www.elsevier.com/locate/surfcoat

Calculation and measurement of the time dependent erosion rate of electromagnetic steered rectangular arc cathodes

Otmar Zimmer[a,*], Jörg Vetter[b], Nils Rackwitz[a], Peter Siemroth[a]

[a]*Fraunhofer Institute for Material and Beam Technology Winterbergstraße 28, 01277 Dresden, Germany*
[b]*Metaplas Ionon Oberflächenveredelungstechnik GmbH, Am Böttcherberg 30-38, 51427 Bergisch Gladbach, Germany*

Abstract

ProArc is a system for programmable electromagnetic controlling of the arc spot motion on large area flat cathodes in devices for vacuum arc evaporation. Using this system allows one to adjust predefined erosion and deposition profiles and to increase the lifetime of the cathodes. Arc spot traces and erosion profiles have been simulated for various run-modes. The simulation enables an estimation of the local erosion rate dependence on both time and magnetic field strength. The computer program used contains a model for the arc spot behavior under the influence of external magnetic fields. These calculations were compared with measured erosion profiles. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: ProArc; Electromagnetic controlling; Cathodes

1. Introduction

The development of cathodic vacuum arc evaporation began in the 1960s and continued with work on the deposition of hard coatings [1–6]. The development of industrial PVD units has intensified in the last 20 years. The experience of the last 10 years shows that almost all types of tools, many machine parts and parts which require a decorative coating can be treated by the vacuum arc deposition [5,6]. The arc movement at the evaporator surface can be classified as follows: random arc (without external magnetic field); weakly steered arc (a weak external magnetic field is used to define the boundaries of the movement and the local residence duration); steered arc (with a strong external magnetic field used to increase remarkably the integral arc travel velocity) and electrically steered arc (stimulation of the arc movement by a definite change in the electrical connection to the cathode or the anodes). Most of the industrial used arc evaporators are of the weakly steered arc type.

In an outer magnetic field the arc spot motion is defined by three superimposed components. These components are the random walk [7,8], the retrograde motion [9,10] and the Robson-drift [11]. The random walk component is always present. It is only dependent on the cathode material. The magnetically induced motion components depends on the strength of the magnetic flux and on the current of the discharge, or rather its own intrinsic magnetic field. In the case of spot splitting, the newly born spots repel each other.

A logical consequence of retrograde motion and Robson-drift is that arc spots can be guided inside arched magnetic field lines, so called tunnel fields. So the arc tracks can be confined to a closed loop. Fig. 1 shows the geometric conditions. In the area of the arc track the magnetic field lines are parallel to the cathode surface. The arc spot is guided back to the track by the Robson-drift component whereas the random component tends to force it off-track. A magnetic flux of 0.5–5 mT is sufficient to steer the spot in the case of titanium as the cathode material. However, strong tunnel like fields result in erosion with a deep groove. To avoid the deep grooves the external magnetic field must be dynamically modified. This work describes a way to realize a time dependent external magnetic field arrangement. Calcu-

* Corresponding author. Tel.: +49-351-2583-257; fax: +49-351-2583-300.
E-mail address: zimmer@iws.fhg.de (O. Zimmer).

PII: S0257-8972(01)01388-3

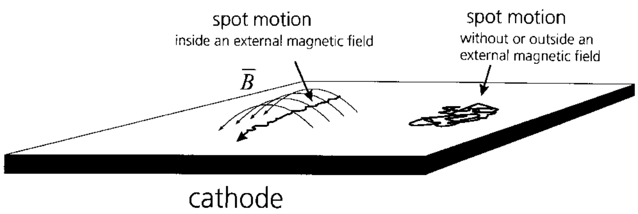

Fig. 1. Steering of the cathode spot in an arched magnetic field (left) and random walk without an external magnetic field (right), $\vec{B}$: magnetic flux.

lations of the erosion profiles were made and compared with experimental measured erosion profiles.

2. Experimental details and results

2.1. Experimental details

Only magnet coils were used for the external magnetic field. A large number of different movement sequences can be created if a certain number of smaller coils are mounted to the backside of the cathode (see Fig. 2). This coil arrangement is called ProArc-system [12]. This external electric-magnetic system consists of the following components:

- Coil array: a number of magnetic coils attached on the rear side of the cathode. These coils produce the magnetic field guiding the arc spot movement.
- Power supply: computer controlled current source. With this current source the magnetic coils can be controlled independently. Each coil current can be adjusted in amperage and direction.
- Computer.
- Software: sets of coil current values can be saved and run by the software. Several sets of coil current values can be combined into sequences or processes, one process step corresponds to a defined track of the arc spot. Within the process-definition the process steps can be organized in repeating loops.

Fig. 3 shows a coating device equipped with a ProArc-System consisting of 24 smaller coils. This device is used in the Fraunhofer-Institute for Materials and Beam Technology in Dresden, Germany. It is used mostly for research and development and for smaller coating series.

An industrial coating unit of the type MZR303U (manufacturer Metaplas Ionon Oberflächenverdelung-stechnik GmbH, Germany) was equipped with a ProArc-system with three coils. On the one hand, this system is considerably limited in flexibility compared to systems with more coils. On the other hand, its design is simple and shows sufficient performance. Due to the simple construction the experiments and the modeling were easy to make in order to compare the theoretical calculation with the experimental results. Fig. 4 shows a schematic drawing of the three coil arrangement.

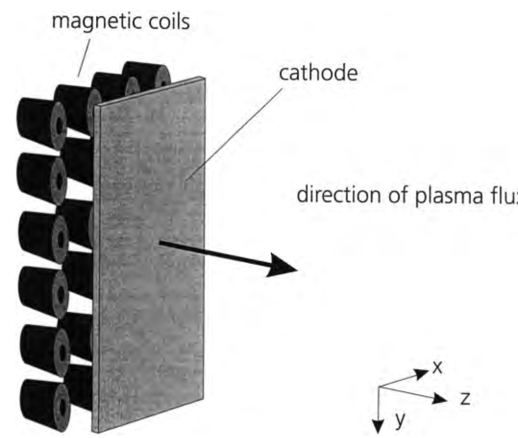

Fig. 2. Conception of the magnetic Arc spot guiding system 'ProArc' with 24 coils.

The coils can be independently controlled. The coil currents can be adjusted in the range from –10 A to + 10 A. The coil settings can be changed with a time resolution of 0.6 s. A special program was developed to investigate the erosion of the rectangular flat Ti-cathode with the dimensions: 450 mm in length and 130 mm in width. Three different settings of the magnetic field were selected by visual observation of the arc track

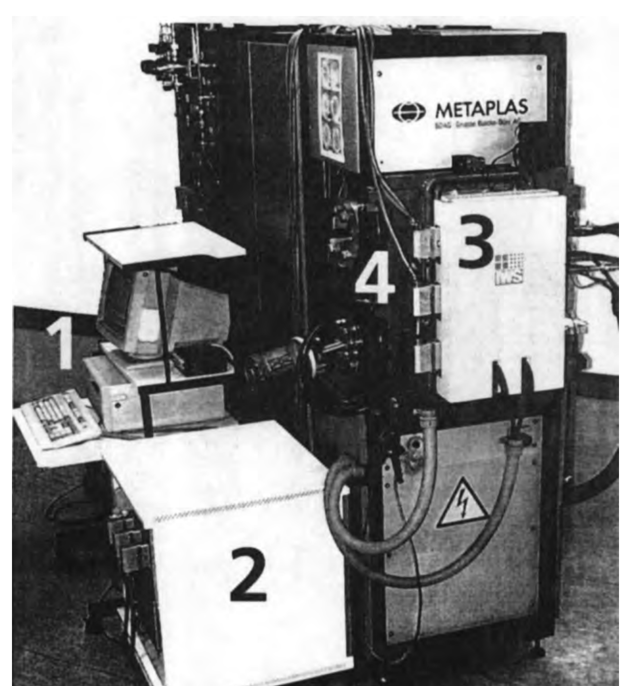

Fig. 3. ProArc-system assembled to a vacuum-arc coating device: 1, computer; 2, multi-channel power source; 3, coil array with 24 coils; 4, coating chamber.

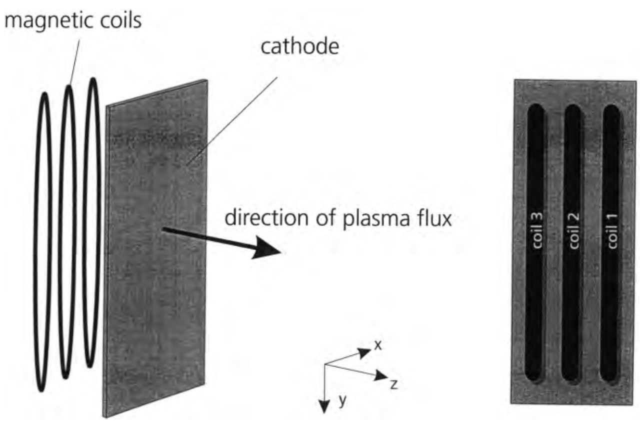

Fig. 4. ProArc-system with three magnetic coils, principle outline an position of the coils.

movement through a window in the chamber. The settings were more or less subjectively chosen. For example, the settings for field 3 of the erosion test are shown in Fig. 5. The settings were cyclically passed by changing it each second. The discharge was operated with a discharge current of 100 A for 54 h altogether ($Q=1.94\times10^7$ C).

A new cathode with a smooth surface has been used. After running the tests the erosion profile of the cathode surface was analyzed. The measurement was done with a grid at 12×47 locations giving a total number of measurement locations of 564. The material loss of the cathode was approximately 0.9 kg. The cathode material was titanium.

2.2. Results of the erosion experiment

The measured erosion profile is shown in Fig. 6. The erosion depth is not totally symmetric as expected from the setting of the magnetic field. A significantly stronger erosion was measured at the upper side and at the right side.

3. ArcSim — a program for simulation of the magnetically steered arc spot motion

Despite the well-known physical and mathematical descriptions of the cathode arc spot it is very difficult to get qualitative and quantitative information about the spot dynamics in dependence on the parameters of the process. Nevertheless, there is a need for good approximations for the arc spot behavior and the coating result, especially for the development of new coating devices. This suggested the development of a simulation software package for the calculation of the arc spot motion to predict the target erosion and its dependence on the external magnetic fields. With this software, called ArcSim [13], it will be easier to optimize relevant process parameters.

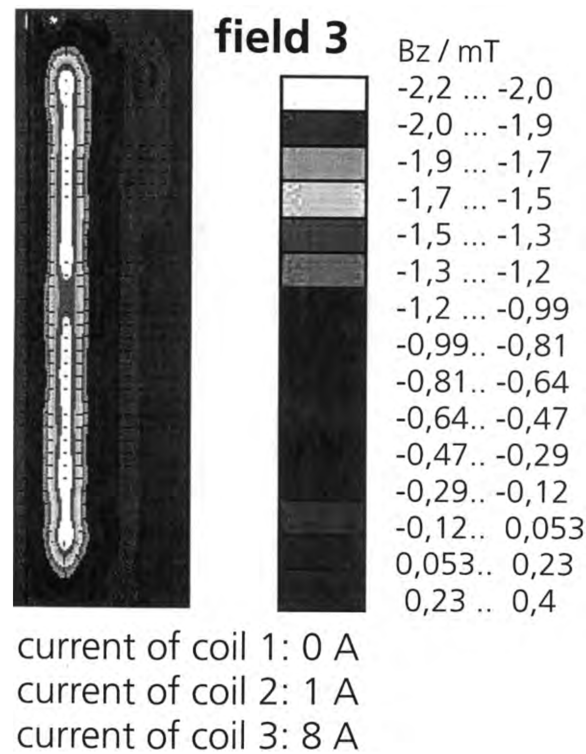

Fig. 5. Example for a magnetic field used for the erosion experiments (field 3): The magnetic components in *z*-direction is coded by color levels, the components in *x*- and *y*-direction by small field lines.

3.1. The mathematical model

During the development of the mathematical model the following characteristics of the cathode spot motion came into consideration:

- random walk;
- retrograde motion: caused by external magnetic fields and caused by magnetic fields of simultaneously existing spots;
- Robson-drift;
- spot splitting;

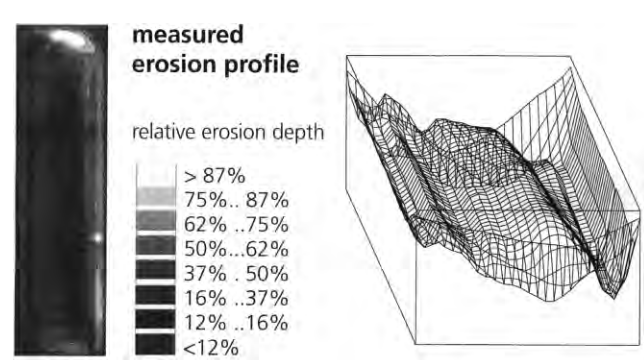

Fig. 6. Erosion profile after 1.94×10^7 C with a discharge current of 100 A. For arc steering the magnetic fields 1–3 were used.

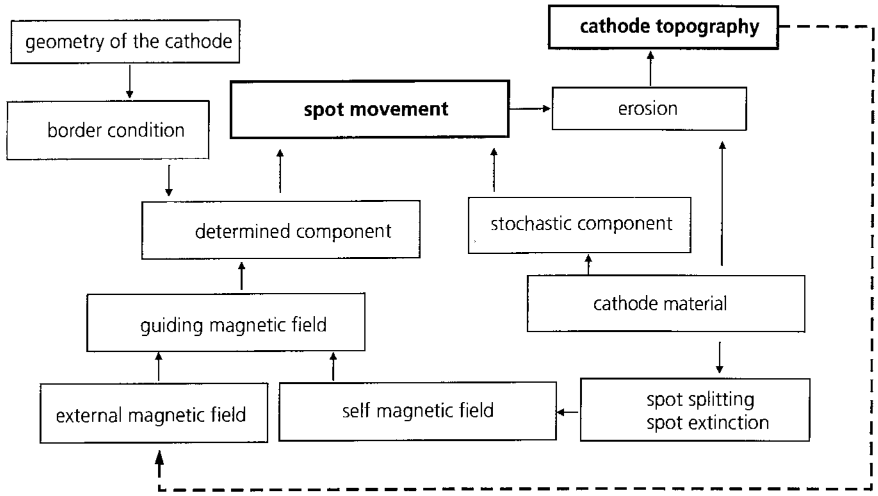

Fig. 7. Components of the arc spot motion model and their correlations between each other.

- spot extinction; and
- changes of cathode surface profile, caused by the local erosion.

Fig. 7 shows an overview of the dependencies. The spot movement is influenced by a deterministic and a stochastic component. This movement causes the erosion and in this way the resulting cathode topography. The stochastic component depends on the cathode material. The boundary conditions and the influences of the external and the self-magnetic field are summarized in the deterministic component. All influences shown in Fig. 7 are implemented in the simulation software package ArcSim. A description of the model and its implementation in detail is given in an earlier paper [13].

3.2. Software package and results

The input parameters are:

- the material and the shape of the cathode;
- the external magnetic field;
- the arc current;
- parameters for spot splitting and extinction;
- the length of an elementary step of spot motion in the calculation; and
- the magnetic speed and the diffusion constant of the spot motion.

These parameters are used to simulate the macroscopic behavior of the cathode spot in the form of the probability of the location of the cathode spot.

The material erosion (mm or g) results from the combination of the material parameters (erosion constant g/C) with the spot location. In the following only the relative erosion profile will be shown. Therefore it is independent from the cathode material and reactive gas phenomena.

3.3. Results of the simulations

Several simulations have been carried out using the magnetic configurations with the three-coil arrangement. Two examples of cathode spot tracks are presented in Fig. 8 showing the field of coil 3. Fig. 8a shows that the spot has the possibility to move outside of the arched magnetic field in that case the spot trace is determined primarily by the random walk (see Fig. 1). Fig. 8b demonstrates the spot movement in the tunnel of the arched magnetic field with less influence from the random walk. The same phenomena were observed during the erosion experiment. During the simulation the residence time of the cathode spots is accumulated for 250×250 positions at the cathode surface. To derive the relative erosion profile (Fig. 9) the profiles for magnetic fields 1–3 have been superimposed. The total simulation corresponds to an actual discharge time of approximately 12 min at an arc current of 100 A. The calculation time using a standard PC was approximately 8 h.

4. Comparison between measured and simulated erosion profile

The comparison between the measured erosion profile (Fig. 6) and the simulated profile (Fig. 9) shows a lot of similarities but also some differences.

Deep erosion on the upper and lower right side and at the right margin can be found in the simulated as well as in the measured profile. The same is true for a flat erosion area at the left side of the cathode and deep erosion on the left margin.

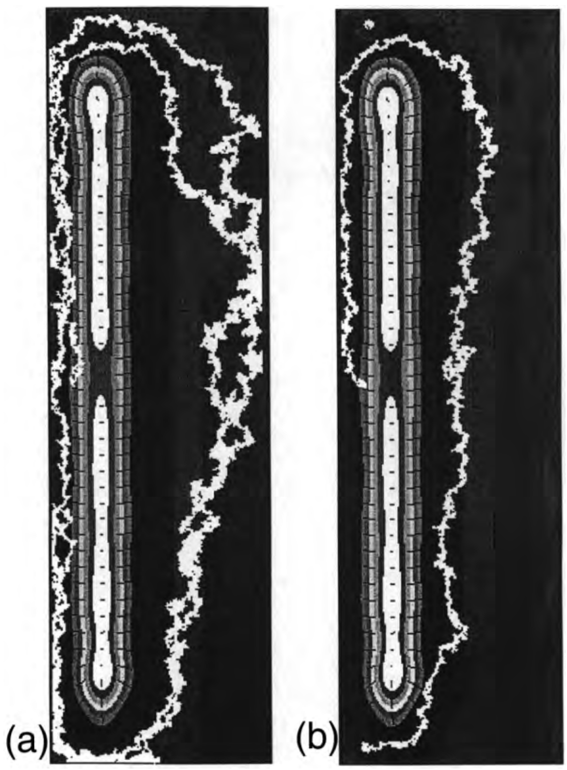

Fig. 8. Samples of calculated arc spot tracks. The used magnetic field is field 3. (a) First example: spot was partially running outside of the magnetic field; (b) second example: spot movement guided in the tunnel field.

Differences can be found in the more uneven profile and the longer presence of the cathode spot at the lower side of the cathode in the simulation.

Trimming of the calculation is necessary to include some boundary conditions in more detail. The calculation does not include the variation of the external magnetic field with the erosion depth of the cathode.

It seems to be also possible that the anode location has an influence at the arc spot motion. This influence is not considered in the mathematical model. It can strongly influence the preferential residence of the cathode spot [14].

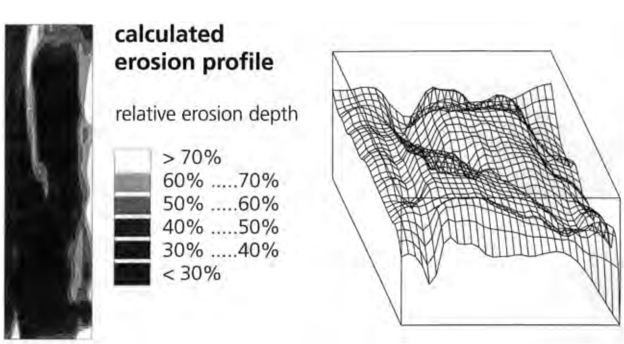

Fig. 9. Relative erosion profile calculated from the simulated spot tracks (Fig. 8). The single profiles were calculated for fields 1–3. This profile was added to the overall profile.

Another potential cause for the differences is the magnetic field used for the calculation. The field distribution was measured at an opened door of the vacuum vessel. The field might change remarkably under the influence of the chamber walls and the location of the cables from the power supply, which are different when the door is closed. In addition the field was measured for a limited number of measurement points. Intermediate values between the measure points were interpolated.

The temperature distribution at the cathode surface might also influence the results. It is also not considered in the mathematical model.

The calculated discharge time was 250 times shorter than the real discharge time due to the limited calculation power of the used computer. This can be the reason of the more uneven profile in the calculation. The random walk component can cause a more even profile for longer simulation times.

5. Conclusions

In the present work the state-of-the-art knowledge about the cathode spots is used for a simulation. The software opens the possibility to compare the modern theories with experimental results.

The magnetic field strength of approximately 2 mT is sufficient to steer the arc movement.

The calculation results of the erosion profile fit in the first approximation the experimental results. This proves the suitability of the physical model. The model also shows the sensitivity of the erosion to the magnetic steering fields. The calculated spot traces sometimes show the random walk outside the external magnetic field as observed in the erosion experiment. However, some deviations of the erosion depth between the calculation and the experiment were observed. For the calculation of the exact erosion profile further refinement of the model is necessary. Especially the input parameters such as the magnetic field must reflect the real conditions. In addition using the online update of cathode profile during the calculation run time can improve the calculation results.

References

[1] A.A. Snaper, US Patents 3 625 848 1971 and 2 836 451, 1974.
[2] L.P. Sablev, N.P. Atamansky, V.N. Gorbunov, J.I. Dolotov, V.N. Lutseenko, V.M. Usov, US Patents 3793 179 and 3 783 321, 1974.
[3] I.I. Aksenov, V.G. Bren, V.G. Padalka, V.M. Koroshikh, Sov. Phys. Tech. Phys. 23 (1978) 651.
[4] H. Randhawa, P.C. Johnson, Surf. Coat. Technol. 31 (1987) 303.
[5] J. Vetter, Surf. Coat. Technol. 76/77 (1995) 719.

[6] R.L. Boxmann, P.J. Martin, D.M. Sanders, Handbook of Vacuum Arc Science and Technology, Noyes publications, New Jersey, 1995.
[7] J.E. Daalder, J. Appl. Phys. 16 (1983) 17–27.
[8] E. Hantzsche, B. Jüttner, H. Pursch, J. Appl. Phys. 16 (1983) L173–L177.
[9] J. Stark, Z. Phys. 4 (1903) 440.
[10] C.J. Gallagher, J. Appl. Phys. 21 (1950) 768–771.
[11] A.E. Robson, Proceedings of IVth Int. Conf. Phen. Ion. Gases, IIB, 1959, pp. 346–349.
[12] O. Zimmer, P. Siemroth, T. Schülke, J. Vetter, Surf. Coat. Technol. 94-95 (1997) 592–596.
[13] N. Rackwitz, ECMI Newsletter. Number 26, Oct., 1999, p. 15–19.
[14] H. Tamagaki, European Patent EP00492592B1, 1992.