Proceedings of the International Conference
Nanomaterials: Applications and Properties
Vol. **3** No 1, 01PISERE01(4pp) (2014)

Development of Magnetic Field-enhanced Vacuum Arc Deposition in China

Yanhui Zhao[1], W.C. Lang[2], J.Q. Xiao[1,*], B.H. Yu[1], J. Gong[1], C. Sun[1]

[1] *Institute of Metal Research, Chinese Academy of Sciences, 110016 Shenyang, PR China*
[2] *Key Lab of Material Processing and Mould Technology, Wenzhou Vocational & Technical College, 325035 Wenzhou, PR China*

(Received 12 February 2014; published online 29 August 2014)

This paper reviews the latest research and development in China for magnetic field-enhanced vacuum arc deposition (MFE-VAD). China has developed some new technologies in MFE-VAD. These technologies are all based on the interaction between the magnetic field and cathode arc spot (and arc plasma). An external magnetic field can be applied to steer the cathode spot motion including axisymmetric magnetic field (AMF), transverse rotating magnetic field (TRMF) and coupling magnetic field (CMF). The transverse component of AFM can accelerate the cathode spot motion. The TRMF covered the whole cathode was generated by stationary three-phase windings carrying three-phase alternating currents. The CMF was designed to improve the increasing of plasma density and the collisions between ion and droplet-particls (DPs) charging, and as well as further purify the DPs.

Keywords: Vacuum arc deposition, Magnetic field, Cathode spot motion, Droplet-particles reduction

PACS numbers: 52.40. – w, 52.25. – b

1. INTRODUCTION

Vacuum arc deposition (VAD) has been widely used for deposition of hard protective coatings especially in mechanical field such as cutting tools, moulds and etc. It is characterized with a high current electrical discharge resulting in its high ionization (70 % ~ 80 %), which in turn causes high deposition rate, excellent film density, strong film/substrate adhesion [1-3]. Unfortunately, droplet-particles (DPs) of up to several micrometers in size are also emitted with ionized particles due to the plasma-liquid pool interactions in the cathode spot [4-5]. The emitted DPs usually land on the surface of the prepared films and deteriorate the quality and performance of the films and hindering a broad VAD application. Therefore, DPs contamination has been the most important technological problem and becomes the main obstacle in VAD process [6].

In order to eliminate DPs, several mothods have been presented to solve this droplet problem. The methods can be roughly classified into two types, one in which the generation of the droplets is suppressed, and the other in which the droplets are reduced during their transportation. The former consists of steering arc [7], distributed arc [8] and pulsed arc [9]. The latter includes shielded vacuum arc [10], magnetically filtered vacuum arc [11] and coaxial vacuum arc [12]. Furthermore, some parameters related to this deposition process such as cathode poisoning [13], negative substrate pulse-biasing [14-17] were also provided in order to reduce DPs.

Of all these methods, the external magnetic field-enhanced VAD is a positive mean to reduce DPs generation because it can solve the problem at the origin of the process. It is firmly established that cathode spot is a process related to a rapid sequence of individual ignition and extinction of active emission sites [18-19]. An external magnetic field can be applied to steer the cathode spot motion due to its physical intrinsic characteristics of conduction [20-21]. The so-called' steering arc' is an arched magnetic field, which has been investigated intensively [7, 22-23]. Much work has been done to investigate cathode spot dynamics under different magnetic field component in a vacuum [24-28]. It has been shown that the cathode spot moves at random on the cathode surface in the absence of a magnetic field. The cathode spot moves in a direction perpendicular to the field lines in the reverse direction to the ampere rule (“retrograde motion”) applying a magnetic field parallel to the cathode surface (B//). When applying an acute-angled magnetic field, the cathode spot obeys the “acute angle rule” [29-30], that is to say, the cathode spot is not only superimposed a retrograde motion (corresponding to B// component) but also superimposed on a robson drift, and the direction of the robson drift points to the acute angle area between the surface of the cathode and the magnetic field lines. The acute angle rule is available for restricting the motion direction and occurrence of the cathode surface of the cathode spot, which is significantly important for steering of cathode spot motion and uniform etching the cathode target [31]. When applying an axisymmetric magnetic field (AFM), the cathode spot will suffer from the retrograde motion resulted from the B// component and the acute-angled magnetic field (in presence of acute angle of cathode target edge). In the present paper, some experimental results about magnetic field-enhanced vacuum arc deposition in China will be presented and the results of film deposition applying different kinds of magnetic field are also given.

2. STEERED VACUUM ARC BY IMPLYING AMF

Lang et al. [31-32] designed an AMF enhanced VAD equipment, as shown in Fig. 1. In this design, an adjustable electromagnetic coil enclosed with a coaxial cylinder of magnetically soft coating was located behind the cathode (a water-cooled titanium cathode of 60 mm

---

[*] jqxiao@imr.ac.cn

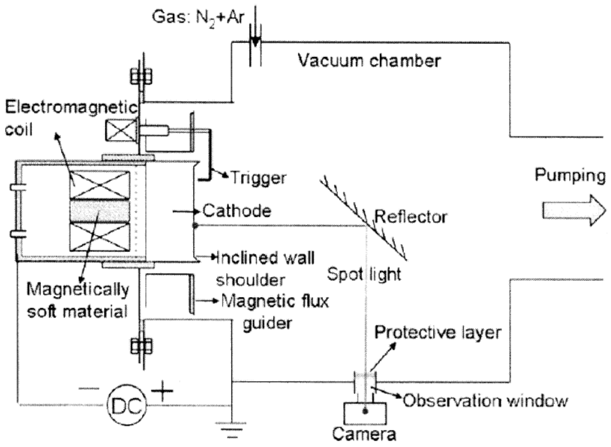

Fig. 1 – Schematic illustration of the AMF enhanced VAD equipment

in diameter and 30 mm in thickness). TiN films were deposited on 1Cr18Ni9Ti stainless-steel specimens with the arc current of 60 A for the deposition time of 30 min. the distribution of the AMF was simulated by using the FEMM 4.2 software package.

An axisymmetric magnetic field can be decomposed into two parts: a transverse magnetic field component perpendicular to the target surface BT and the longitudinal magnetic field component parallel to the target surface BN. Fig. 2 shows the distributions of BT and BN on the cathodic target surface under different field intensities presented by Icoil (coil current). The BT at the edge of target increases with Icoil and the BN at the centre of target increases with Icoil.

It was showed that the AMF intensity strong influences the cathode spot motion. In the case of a weak AMF (< 5 Gs), a big the cathode spot moves randomly and slowly on the cathode target surface. With the AMF increasing, there is an increasing trend for the cathode spot to refine, rotate and drift toward the cathode target edge, exhibiting a chrysanthemum structure, the cathode spot motion pattern changed from a big bright spot to a thinner and longer line. An increase in the BT intensity can accelerate the rotational speed of the cathode spot and increase the arc voltage. With a relatively strong AMF (BT ≈ 30 Gs), the cathode spot rotates near the edge of the cathode surface and is restricted to a circular trajectory.

By applying an AMF with different magnetic field, it can be seen that the DPs number and sizes of deposited TiN films are significantly decreased with the magnetic field intensity increasing. Furthermore, the roughness (Ra) of the TiN films is apparently reduced with the magnetic field intensity increasing, from 0.16 μm at 0 Gs to 0.05 μm at 30 Gs. It is concluded that DPs reduction could significantlyimprove the surface quality of films. In addition, the results of deposited (Ti, Al)N films using the same processing is basically the same as those of TiN films [33].

3. STEERED VACUUM ARC BY IMPLYING TRANSVERSE ROTATING MAGNETIC FIELD (TRMF)

Most of the magnetic fields were designed to be static and quasi-static in steered vacuum arc deposition. In general, one and more permanent magnets were usually used to steer the cathode spot motion located behind the cathode target. Furthermore, one or more electromagnetic coils instead of permanent magnets were also applied to steer the cathode spot motion. These designed magnetic fields greatly steer the cathode spot motion and reduce the DPs pollution in the prepared films. However, the cathode spot cannot disperse through all the area of the cathode target surface, which cause low utilization of the targets and high cost for films production when using the above-mentioned static magnetic fields.

Lang [34] designed a transverse rotating magnetic field source and its producing equipment. Using FEM, the magnetic field configuration was simulated, as shown in Fig. 3. In this design, several magnetic poles ($4n$ or $3n$, $n \geq 1$) with the same angle differences in space were used, and each pole was equipped with several excitations coil windings (2 or 3). All the poles with windings were configured to a coaxial flange driven by an adjustable rotation speed motor. Fig. 3b shows schematic diagram of the poles rotate at different position in one period. In the specific design, a bipolar symmetric rotating magnetic field (RMF) with N-S magnetic pole was thus produced.

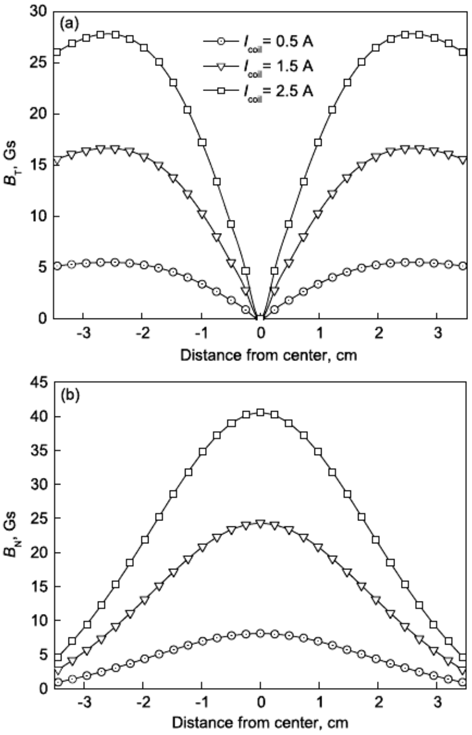

Fig. 2 – Distributions of BT (a) and BN (b) on the cathodic target surface under different field intensities presented by Icoil (coil current)

Fig. 4 shows transient distribution of magnetic field at different times simulated by FEM. It can be seen that magnetic flux showed an almost homogeneous distribution, especially at the centre of the magnetic field producing equipment. By changing the rotating frequency and the amplitude of the coil exciting current (these two parameters can be adjusted independently), the speed of rotation and the magnetic intensity could be regulated continuously.

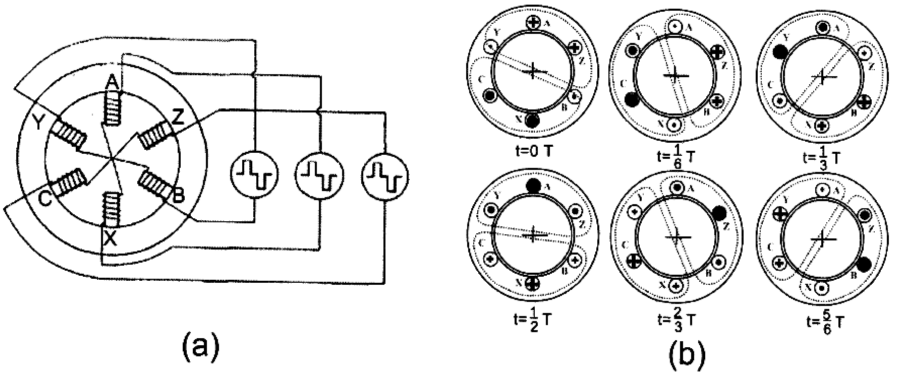

Fig. 3– Schematic diagram of rotating magnetic field generation

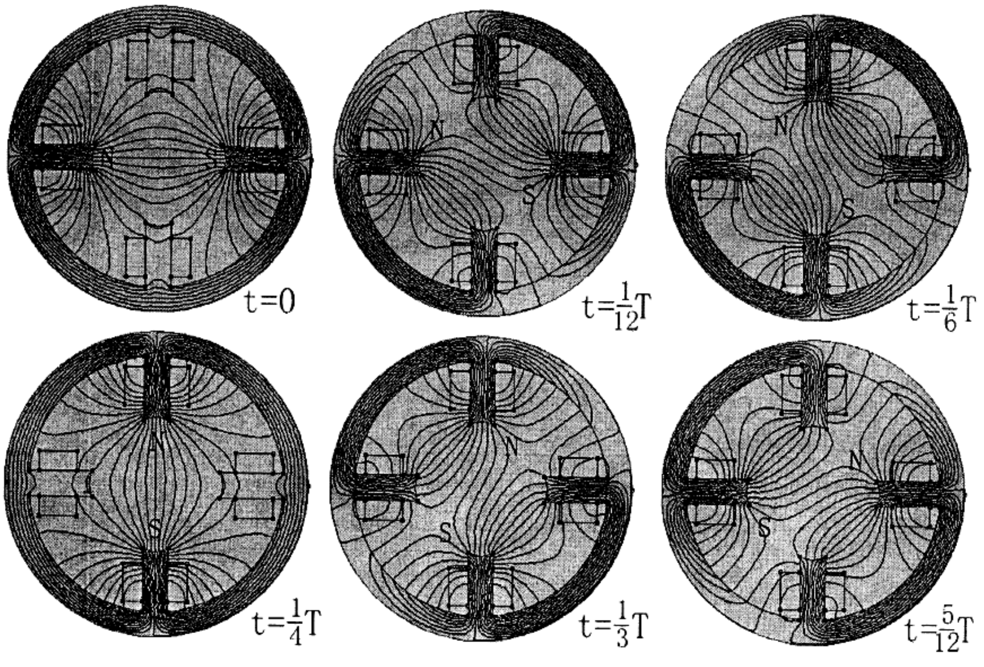

Fig. 4 – Transient distribution of the magnetic field at different times

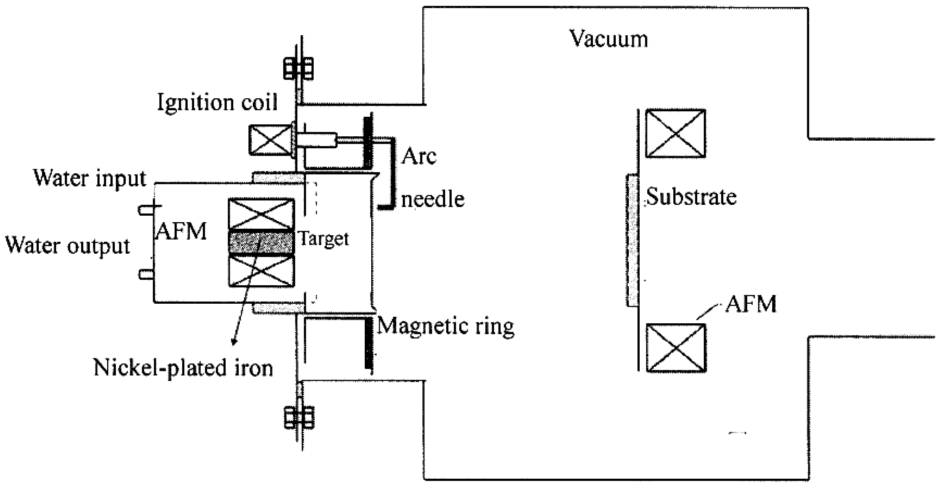

Fig. 5 – Schematic diagram of the case 1 of implementation of coupled magnetic field enhanced deposition

By applying the TRMF, TiN films by different frequency and intensity of the rotating transverse magnetic field were deposited. The results showed that the size and number of DPs on the surface of TiN films were reduced with the frequency and coil excitation current decreasing. It also showed that the distribution of DPs was closely related to the state of arc spot motion. With the intensity and frequency of the RTMF increasing, the transient area of the spot arc on the target surface was also increased, which reduced the emission of DPs.

4. STEERED VACUUM ARC BY IMPLYING COUPLING MAGNETIC FIELD

The electromagnetic field can not only steer the cathode arc spot motion but also control the motion trajectory of arc plasma after being produced by arc discharge. Lang [35] designed a coupling magnetic field including an AFM placed behind the cathode target and an AFM located behind the substrate, as is shown in Fig. 5.

And the results of the coupled magnetic field configuration and only TRMF configuration simulated by FEM showed that without an AFM located behind the substrate, the arc plasma from the cathode target surface acted as a point source. In this conventional processing, the magnetic field configuration behind the cathode target is inhomogeneous, causing the uneven spatial distribution of the plasma during the transmission. In this case, the thickness of films at different positions on the substrate could be non-uniform. But when applying the coupled magnetic field configuration, especially applying an AFM located behind the substrate, the transmission during the plasma space will be limited to a quite centralized area, which will enhance the plasma density and uniformity near the substrate. As a result, the deposition rate and uniformity of the deposited films will be greatly improved.

It showed that with the increase of the strength of coupled magnetic field, the number and the size of DPs on TiN films surface have been greatly reduced. The reason for this is because the coupling magnetic field will improve the increasing of plasma density and the collisions between ion and DPs charging, and the substrate bias will rebound the charged DPs and then less DPs will land onto the surface of substrate. The plasma under the influence of coupled magnetic field, which has enhanced the interaction between the plasma and the DPs as well as further purified the DPs. Moreover, the deposition rate of film has been exponentially increased. Summary and Outlook Based on the interaction between the magnetic field and arc spot (and arc plasma), an external magnetic field can be applied to steer the cathode spot motion including axisymmetric magnetic field (AMF), transverse rotating magnetic field (TRMF) and coupling magnetic field (CMF). The transverse component of AFM can accelerate the cathode spot motion. The TRMF covered the whole cathode was generated by stationary three-phase windings carrying three-phase alternating currents. The CMF was designed to improve the increasing of plasma density and the collisions between ion and DPs charging, and as well as further purify the DPs. Different kinds of magnetic fields will play different roles on the cathode spot motion and motion trajectory of arc plasma, which depends on the specific application conditions.

AKNOWLEDGEMENTS

This work was supported by the National Natural Science Foundation of China (granted No. 51171197).

REFERENCES

1. P.J. Martin, A. Bendavid, *Thin Solid Films* **394**, 1 (2001).
2. M. Mack, *Oberflächentechnik*, (Verlag Moderne Industrie: 1990).
3. D.M. Sanders, A. Anders, *Surf. Coat. Technol.* **133-134**, 78 (2000).
4. R.L. Boxman, S. Goldsmith, *Surf. Coat. Technol.* **52**, 39 (1992).
5. S. Anders, A. Anders, I.G. Brown, *IEEE T. Plasma Sci.* **21**, 440 (1993).
6. F. Sanchette, C. Ducros, T. Schmitt, P. Steyer, A. Billard, *Surf. Coat. Technol.* **205**, 5444 (2011).
7. P.D. Swift, *J. Appl. Phys.* **29**, 2025 (1996).
8. A.I. Vasin, A.M. Dorodnov, V.A. Petrosov, *Sov. Technol. Phys. Lett.* **5**, 634 (1979).
9. K. Kimura, H. Takikawa, T. Sakakibara, *Appl. Plasma Sci.* **7**, 3 (1999).
10. Y. Taki, T. Kitagawa, O. Taka, *J. Mater. Sci. Lett.* **16**, 553 (1997).
11. I.I. Aksenov, V.A. Belous, V.G. Padalka, V.M. Khoroshikh, *Sov. J. Plasma Phys.* **4**, 425 (1978).
12. S.Y. Chun, A. Chyahara, A. Kinomura, N. Tsubouchi, C. Heck, Y. Horino Y, *Jpn. J. Appl. Phys.* **38**, L467 (1999).
13. R. Hovsepian, D. Popov, *Vacuum* **45**, 603 (1994).
14. Y.H. Zhao, G.Q. Lin, C. Dong, L.S. Wen, *J. Mater. Sci. Technol.* **21**, 423 (2005).
15. Y.H. Zhao, G.Q. Lin, C. Dong, L.S. Wen, *J. Mater. Sci. Technol.* **25**, 681 (2009).
16. G.Q. Lin, Y.H. Zhao, H.M. Guo, D.Z. Wang, C. Dong, L.S. Wen, *J. Vac. Sci. Technol. A* **22**, 1218 (2004).
17. M.D. Huang, G.Q. Lin, Y.H. Zhao, L.S. Wen, C. Dong, *Surf. Coat. Technol.* **176**, 109 (2003).
18. A. Anders, *Thin Solid Films* **502**, 22 (2006).
19. A. Anders, *Vacuum* **67**, 673 (2002).
20. D.M. Sanders, D.B. BoerckerM.S. Falabella, *IEEE T. Plasma Sci.* **PS-18**, 883（1990）.
21. R.M.S. John, S.G. Winans, *Phys. Rev.* **94**, 1097 (1954).
22. S. Ramalingam, C.B. Qi, K. Kim, US patent: 4673477 (1987).
23. P.J. Walke, R. New, C.M. Care, *Surf. Coat. Technol.* **59**, 126 (1993).
24. V.N. Zhitomirsky, R.L. Boxman, S. Goldsmith, *Surf. Coat. Technol.* **68-69**, 146 (1994).
25. P. Siemroth, B. Schultrich, T. Schülke, *Surf. Coat. Technol.* **74-75**, 92 (1995).
26. J.K. Kim, K.R. Lee, K.Y. Eun, K.H. Chung, *Surf. Coat. Technol.* **124**, 135 (2000).
27. N.R. Walke, C.M. Care, *Surf. Coat. Technol.* **59**, 126 (1993).
28. Z.M. Yang, Q.L. Zhang, C.Y. Zhang, Y. Sun, B.J. Ding, *Phys. Lett.* **A353**, 98 (2006).
29. A.E. Robson, *Proc 4th Int Conf on Phenomena in Ionized Gas*. Uppsala, **1**, 340 (1959).
30. B.F. Coll, D.M. Sanders, *Surf. Coat. Technol.* **81**, 42 (1996).
31. W.C. Lang, J.Q. Xiao, J. Gong, C. Sun, R.F. Huang, L.S. Wen, *Acta. Metall. Sinica.* **46**, 372 (2010).
32. W.C. Lang, J.Q. Xiao, J. Gong, C. Sun, R.F. Huang, L.S. Wen, *Vacuum* **84**, 1111 (2010).
33. J.Q. Xiao, W.C. Lang, J. Gong, C. Sun, R.F. Huang, L.S. Wen, *Phys. Proc.* **18**, 193 (2011).
34. W.C. Lang, *Adv. Mater. Res.* **337**, 70 (2011).
35. W.C. Lang, *Adv. Mater. Res.* **399-401**, 2018 (2012).