High deposition rate magnetrons – innovative coating technology: key elements and advantages

V. S. Mitin, E. I. Sharipov* and A. V. Mitin

An innovative coating technology based on ion plasma magnetron sputtering physical vacuum deposition (IMPS-PVD) method has been developed to produce new complex coatings to meet the constantly growing demand of advanced industries, with a view to replacing chemical coating methods owing to their ecology danger and to complement/replace high temperature PVD methods. The high deposition rate magnetron (HDRM) technology has initiated a rebirth of mosaic targets as the key component leading to a big increase in the design accuracy of both targets and coatings to be deposited.

1 **Keywords: Magnetron, vacuum, plasma, coating technology**

Introduction

At present, among the well known physical vacuum deposition (PVD) technologies, ion plasma magnetron sputtering (IPMS) has been taking a leading role in expanding the variety of coatings.[1–3] Within IPMS-PVD technologies the closed field unbalanced magnetron sputter ion plating (CFUBMSIP) method patently by Teer Coatings Company[4] has made outstanding contributions to the advancement of PVD based surface engineering leading to the deposits of unbeatable protective coatings in the thickness range of 0·5–4·0 μm. To deposit the coatings with a large set of alloying elements, a multicathode scheme has been proposed/developed. A magnetron installation with 4–6 magnetron sputter systems (MSS) was a deposition rate (DR) R_d for metallic coatings – 10–15 μm h^{-1} and chemical compositions and composites <5 μm h^{-1} (Refs. 1,3,5,6) under a power density D_p of 5–20 W cm^{-2}.

CFUBMSIP can also be used for depositing materials which are difficult or impossible to melt jointly, such as Cr–C, Cu–C, etc.[3] These unbalanced MSS allow for the successful combination of processes involving both surface ionic activation and the deposition of highly dense films of excellent adhesion with a specific composition.

The major competitors to the IPMS-PVD technology are the methods based on heating to the melting–boiling–evaporation point of the materials to be deposited, e.g. thermal (TD) PVD,[7] electron beam (EB) PVD[8] and laser beam (LB) PVD9 techniques which are widely used for coating mainly pure metals. Such a limitation is linked to the key issue of those methods – evaporation. When it comes to evaporating multicomponent compositions – nitrides, carbides and oxides – considerable technological problems arise related to different melting temperatures of the components and their vapour pressure. Naturally, owing to these differences the films are sputtered unevenly. To avoid these problems, multicrucibles evaporation schemes need to be used for each component from its own crucible[10] or special crucibles used involving permanent feeding of the components needed are employed.[11] It is obvious that such units for depositing multicomponent coatings using the above mentioned schemes are not only very expensive but are also highly complicated from both production and control standpoints.

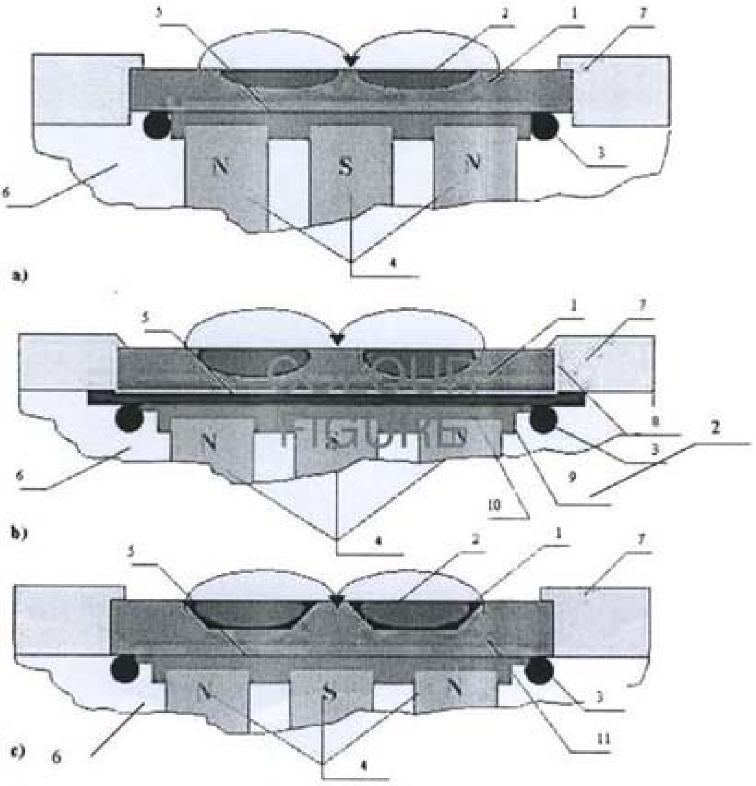
In the 1970s in the former USSR, at the beginning of the R&D activities, the search for thick (more than 20–30 μm) coatings started. These were needed to be 2 deposited onto critical parts of atomic power stations, i.e. energy supplying components to secure considerably longer service life, as well a safer environment for workers and the local population. These activities resulted in the development of a new HDRM technology as a separate but integral part of the IPMS-PVD method. To take advantage of the IPMS-PVD method to deposit complex multicomponent coatings composites, blends of various metals with different chemical elements possessing unique properties were used to considerably expand the application range of the whole IMPS method. This work resulted in a drastic increase in R_d up to 2 μm min^{-1} and higher owing to the D_p of 40–500 W cm^{-2} used. This led to coating films with thickness of 10–100 μm and above.

The above data provide HDRM technology with the possibility to successfully compete economically and technically with the conventional coating methods, namely electrochemical deposition (ECD) and chemical

Centre Science–Knowledge Technological and Social Innovations (NETSI), 9/4–61 Marshal
Vassilevsky street, Moscow 123098, Russia

*Corresponding author, email emish777@lycos.co.uk

Published by Maney on behalf of the Institute
Accepted 10 November 2005
DOI 10.1179/174329406X85038



a target material of high heat conductivity; *b* target material of high melting, low mechanical strength and porous; *c* target material is low melting point alloy

1 Scheme for target cooking in HDRMSS: 1 target, 2 max erosion zone, 3 viton sealing ring, 4 magnetic system, 5 water cooling current, 6 cathode body, 7 target holder, 8 vacuum air jacket, 9 Cu membrane, 10 solder stratum, 11 target body

vacuum deposition (CVD). Additionally, the HDRM technology possesses the key advantage of coating composition diversity as well as its ability to sputter thick films at highly productive rate.

HDRM: key elements, advantages, prospects

With a view of having IPMS-PVD thick films coated at an industrially acceptable production rate (comparable with chemical deposition processes), the DR has to be drastically increased.[12] To this end a new high DR magnetron sputtering system (HDRMSS) has been designed to exceed the sputtering rate of 10 nm s^{-1} (0·6 μm min^{-1}), which requires D_p of 10^2–10^3 W cm^{-2}. To secure the latter, a magnetron sputtering system with a balanced magnetic field and direct target cooling has been experimentally selected. The choice was conditioned by two major physical factors: a material DR which is linearly linked with Power density and a power density limit which is connected with a target cooling system and its heat conductivity.

Based on the research and development experience, the key approaches to the design of HDRMSS are:

(i) in order to secure the proper conditions for power density input/concentration in the discharge zone onto the target surface, the optimal correlation between the chamber working pressure P and the magnetic field induction B of the magnetron sputtering (MS) magnetic system needs to be ascertained;

 it has been established that the magnetic field induction B of 0·03–0·1 T ensures the effective conditions for ionisation, plasma discharge concentration and its maximum closeness to the target surface to provide discharge ignition and a stable MS system working under a considerably lower chamber working pressure P and minimal deposition distance of 5–10 mm; under $B>0·05$ T, the plasma discharge with a current density D_c up to 3000 mA cm^{-2} (or D_p ≈1200 W cm^{-2}) is successful; the working gas chamber pressure of AR is experimentally selected to correspond with the max DR while bearing in mind the MS system design and chamber volume 3 4

(ii) an effective cooling system for the working target (max erosion zone) is essential and needs to be

Table 1 HDRIPMS basic characteristics

No. (П/П)	Design characteristics							Discharge energy characteristics			
	Possible cathode amount on flange, s^{-1}	Target types basic sizes, mm			Magnetic system (MS)			Power			
		Disc dia.	Tube max L Ø	Plates $L \times B$	MS type, magnet material	Target max erosion zone, mm^2	Minimum sputtering distance, mm	Max, KW	Density, W cm^{-2}	Current discharge max, A	Voltage discharge (min–max), V
1	2	3	4	5	6	7	8	9	10	11	12
1	5	50	–	–	Immovable	6·5	25	2	<300	5	450–600
2	4	100	–	–	$SmCo_5$	25·6	25			10	
					NdFeB,						
					$SmCo_5$						
3	2	–	–	300 × 70	Immovable	108	35			20	350–600
4	2	–	–	350 × 70	FeBa	118	35	10	<250	25	
5	2	–	–	500 × 70	NdFeB,	155	35	50		35	
6	1	–	–	750 × 80	$SmCo_5$	216	35			45	
					–						
					–						
					–						
7	1	–	–	500 × 80	Movable $SmCo_5$	36	25	12	<500	20	350–700
8	1	–	–	750 × 80	Movable $SmCo_5$	36	25	12	<500	20	350–700
9	1	–	–	1500 × 100	Immovable $SmCo_5$	410	35	70	<200	<100	350–600
10	1	–	10–50	–	Movable	1 × 4 cm^2	10	2		5	
11	1	–	25	–	$SmCo_5$	2 × 4 cm^2	10	10	<500	15	250–350
12	1	–	25–100	–	Movable	3 × 11 cm^2	10		<1200	25	
			25		$SmCo_5$						
			25–100		Movable						
			50		$SmCo_5$						
13	1	–	40	–	Movable $SmCo_5$	6 × 10 cm^2	10	25		35	250–350

defined; According to Ref. 13, the energy effectiveness E_E is equal to $1–3 \times 10^{-9}$ kg J^{-1} for the HDRMSS ion sputter process and 1×10^{-8} kg J^{-1} for the EB-PVD method that makes the two processes both quite comparable and competitive; this is confirmed by comparing the transformation coefficients (TC) to bring the power directly for sputtering (HDRMSS-PVD) or evaporation (EB-PVD); the TC equals: 60–70% for the former and 5–10% for the latter; it also means that the HDRMSS-PVD heat charges onto targets are considerably lower than the EB-PVD charges onto crucible with the material to be evaporated/deposited; the TC figures indicate that target cooling in the HDRMSS is not too problematic. Figure 1 schematically displays the target cooling of HDRMSS. The full description of the latter is given in Refs. 13 and 14[13,14]

(iii) it is vital to select correctly the basic geometrical parameters of the targets: the diameter thickness for round and width thickness for planar targets. For a directly cooled target its diameter must be <150 mm and its width <100 mm.

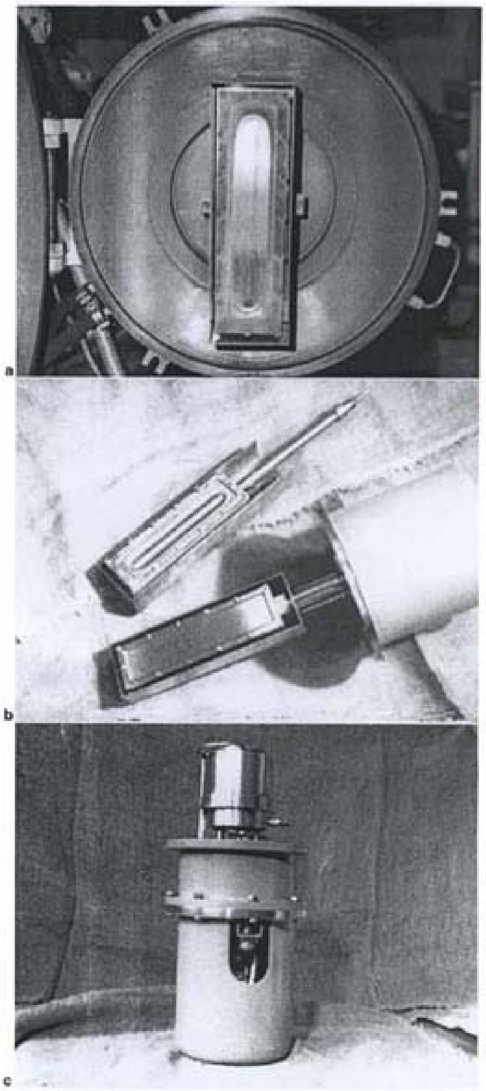
As a result of our extensive research and experience in working with HDRMSS, two design types of HDRMMS were defined: HDRMSS exploited under PD up to 500 W cm^{-2} and ultra HDRMSS employed under power density in the range of 1200–3000 W cm^{-2} with movable magnetic systems (Table 1) (Fig. 2). In the two groups, three types of target are used, namely round discs, plates and tubes. The minimum permissible distance between a target and an article to be coated is 5–10 mm.

It should be also noted that when the magnetron sputtering under the D_p is higher than 40 W cm^{-2} or a D_c 50–80 mA cm^{-2}, the following effects occur[Fig.3]:

(i) 'pulverisation' of the particles up to a few micrometres in size from target materials takes place(metallic as well as ceramic), owing to gaseous impurities and non-metallic inclusions; by using modern vacuum metallurgical technologies like double vacuum (rolling, forging, annealing, etc) melting for manufacturing target materials, the latter do not pulverise even when the D_p is considerably $\gg 100$ W cm^{-2}

(ii) 'premelting' occurs at a certain critical temperature T_{cr}, just before the surface of the target material melts is reflected by a growth in the discharge potential and the discharge current goes down; it is thought that the effect is connected with lowering of the sputtering coefficient by 1·5 times; this arises because being close to melting, the target sputtered surface becomes atomic, and inter atomic links are strengthened; after the target material has melted a reverse process takes place: the current drastically grows owing to additional ionisation of the sputtered material vapours and the voltage declines

(iii) 'impulse action' of the high power density plasma current into the target material. This happens in the movable magnetic systems aimed at substantially increasing the effectiveness of the HDPMSS process; to achieve the impulse action it is necessary to select a working regime to avoid reaching T_{cr}, on the target material surface; this involves choosing both the speed of magnetic system reverse movement (30–50 mm s^{-1}) and the number of magnetic systems should not be less than 1/500 mm.

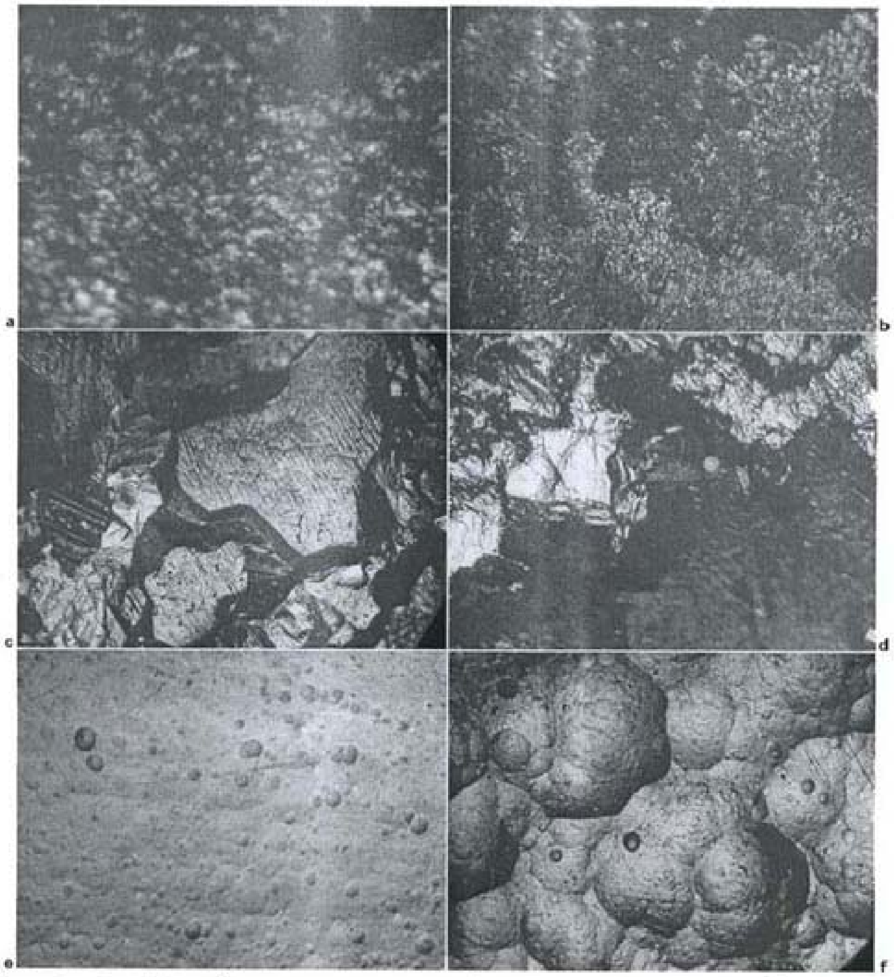


a immovable magnetic system; *b* movable magnetic system; *c* movable target

2 Basic HDRM types

Having made a study analysis of the basic elements of HDRMSS full scale R&D work over the deposition process was carried out.

It has to be mentioned that such a deposition process has the following characteristics: high condensation speed/coating deposition and consequently high productivity; and formation of a great number of crystallisation nuclei with significantly low critical sizes leading to the



a Mo powder, D_p>150 W cm^{-2}; *b* Mo powder, D_p<20 W cm^{-2}; *c* Y–EB remelting, D_p>150 W cm^{-2}; *d* Y–ED remelting, D_p<20 W cm^{-2}; *e* stainless steel, D_p>150 W cm^{-2}; *f* stainless steel, D_p<20 W cm^{-2}

3 Target surface microstructure in sputtering zone, targets made of 8 9

creation of coatings/films with ultra dispersed and amorphous states. The intensive atomic conditions also experience the deposition and formation rates of the coatings owing to the higher energy of neutral atoms sputtered, together with the possibility for partial utilisation of ionised atoms. In addition, the temperature of thermal activation for the substrates could be lowered
6 7 to 0·15–0·35T° melt comparing with 0·25–0·45T° melt for EB-PVD process. It should be noted that the basic surface activation for HDRMSS is ionic treatment, which is important to produce thin coatings of 0·1–5 μm.

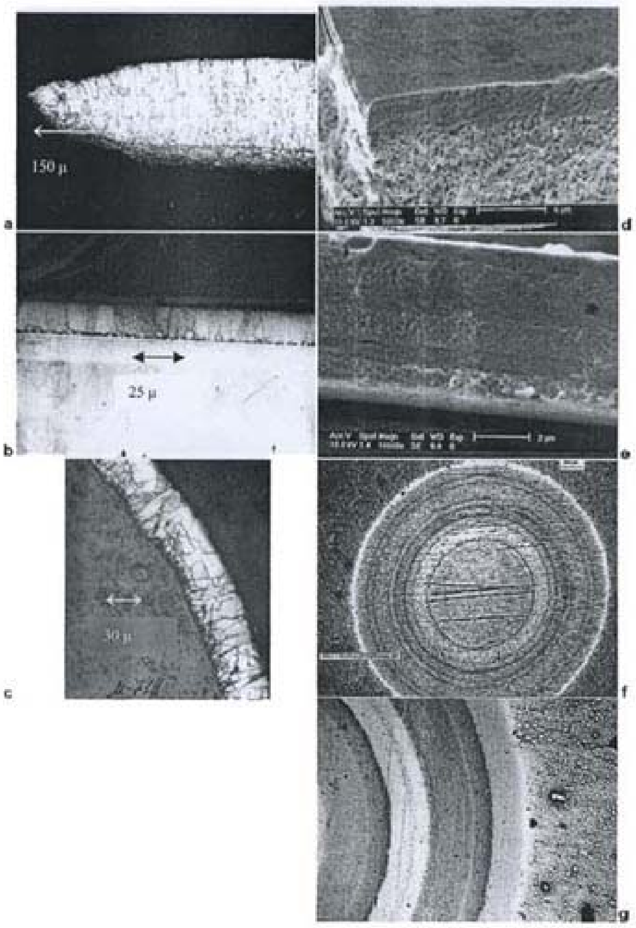
Therefore, high DR ion plasma magnetron sputtering systems (HDRIPMSS) of D_p=40–500 W cm^{-2} and more have been developed. An HDRM magnetron installation with 4–6 such MSS provides an R_d of up to 150 μm h^{-1} for metallic coatings and 50–80 μm h^{-1} for composite and complex composition coatings. The latter paves the way for having the necessary equipment to deposit high temperature protective coatings of 50–120 μm thickness and a surface roughness R_a of 1·29 μm onto critical parts of gas turbine engines used at temperatures around 1100–1150°C.[Fig.4]

More than 20 years of intensive R&D work on HDRM technology has resulted in:

(i) a technology which is industrially acceptable, possessing all the necessary modern aspects needed; it is ecologically and operationally safe, easy to operate and control, and can be combined with other PVD methods/installations

(ii) technology productivity is practically the same or even higher relative to chemical deposition and high temperature PVD methods

(iii) the HDRM method allows for the deposition of practically any materials: magnetic, non-magnetic, refractory, low melting/easy fusible, mono- and multicomponent, metal ceramic and ceramic.



a HDRM-PVD substrate hot surface, Nb 150 µm, T_{sur}=1200°C, after elongation test; *b* HDRM-PVD substrate hot surface, Mo 25 µm, T_{sur}=820°C, 18–10 steel substrate; *c* HDRM-PVD substrate hot surface, Al_2O_3 30 µm, T_{sur}=1500°C, ceramic substrate; *d* thermal–ionic activated substrate surface, HDRM-PVD+ARC-RVD/Multi (6) layered composition of 6 µm in total (each layer=1 µm), (AlTi)N, HDRM (1,3,5 layers) and TiN_x ARC-PVD (2,4,6 layers); *e* thermal–ionic activated substrate surface, 50 µm multilayered coating; *f* thermal–ionic activated substrate surface, 35 µm multilayered coating of metal–ceramics rotation

4 Microstructure of coatings being deposited with R_d=0·5–10 µm min^{-1}

It could be also added that HDRM can operate over an incomparably wide temperature range of 20-1500°C, as well as providing for upgrading target, coating design accuracy and simplifying process control.

Acknowledgements

The authors express their deep gratitude to Dennis Teer and his staff for invaluable assistance in every respect. Also thanks are due to NETSI colleagues for providing all the necessary technical support.

References

1. P. Kelly and R. Arnell: Vacuum, 2000, **56**, 159–172.
2. G. Kienel, B. Meyer and W. Munz: *Vacuumtechnik*, 1981, **30**, 236–246.
3. S. Yang and D. Teer: *Surf. Coat. Technol.*, 2000, **131**, 412–416.
4. D. Teer:UK Patent No. 2258343; USA Patent No. 5554519, **1996**; European Patent: No 0521045, **1992**. 10
5. W. Munz and G. Hessberger: US Patent No. 4426267 C1, **1985**. 11
6. W. Munz, D. Hoffman and K. Harting: *Thin Solid Films*, 1982, **96**, 79.
7. I. A. Raich, L. N. Koltunova and S. N. Fedosov:***Moscow***, *Mashinostroenie*, 1976, 368. 12
8. A. Fenerstein, W. Dietrch and H. Stephan: *Vac. Tech.*, 1984, **50**, 417–423.
9. N. N. Rykalin, A. A. Uglov and A. N. Kokora: Laser material treatment. ***Moscow***, Mashinostroenie, 296. 13
10. V. P. Sinev: *Fisika i khimija obrabotki materialov*, 1978, (4), 136–142.
11. H. Stephan, W. Dietrich, A. Fenerstein and O. Hoffmann: *Metall*, 1981, **35**, 427–431.
12. S. Schiller. V. Heising, K. Goedike: *Vakuum-Technik*, 1978, **21**, (1), 51.
13. V. Mitin *et al.*: Russia Patent No. 2131626, August 1996. 14
14. **Atamanov M., Guseva M.** ***et al.*:*Perspective materials*, 2002, 3, 67-73.** 15