

专题——硬质薄膜与涂层技术

高离化率物理气相沉积涂层的研究进展

钟厉, 龙永杰

(重庆交通大学 机电与车辆工程学院, 重庆 400074)

摘 要: 高离化率物理气相沉积是一种新发展起来的脉冲磁控溅射技术 (HPPMS), 具有溅射靶材原子高度离化与峰值功率超过平均功率等特点。它作为一种新型的离子化物理气相沉积技术, 在国内外已经成为一个研究热点, 其离子体特性、涂层工艺、高功率脉冲放电等备受国内外学者关注。沉积过程中, 离子随着电子碰撞与电荷交换发生电离, 并按照双极性扩散理论进行传递。在不同工作气压条件下, 离子能量分布表现出不同的特点。在放电过程中使用高的峰值功率脉冲 (超出一般沉积技术 2~3 个数量级) 与低脉冲占空比 (0.5%~10%) 实现高电离 (>50%), 从而表现出了优良的结合力, 在控制涂层结构与降低涂层的内部压力等方面有相当大的优势。从 HPPMS 技术制备涂层的应用现状出发, 介绍了高离化率物理气相沉积涂层的特点、优势以及在制备复合涂层和涂层界面优化等方面的研究进展。探讨了高离化率物理气相沉积涂层的未来发展趋势, 对涂层的应用效果进行了分析。

关键词: 高离化率物理气相沉积; 膜基结合力; 涂层特性; 硬质涂层; 峰值功率; 离子能量

中图分类号: TG174.442 **文献标识码:** A **文章编号:** 1001-3660(2017)06-0096-06

DOI: 10.16490/j.cnki.issn.1001-3660.2017.06.015

Study Progress of High Ionization Rate Physical Vapor Deposition Coatings

ZHONG Li, LONG Yong-jie

(School of Mechatronics and Vehicle Engineering, Chongqing Jiaotong University, Chongqing 400074, China)

ABSTRACT: As a new pulse magnetron sputtering technology (HPPMS), high ionization rate physical vapor deposition features have high atomic ionization of sputtering target and high peak power exceeding average power by two orders of magnitude. The new ionization physical vapor deposition technology has become a research hotspot at home and abroad. Its plasma characteristics, coating process and high power pulse discharge have drawn attention of scholars at home and abroad. Ions were ionized with charge exchange along with electron collision during deposition, and were delivered in accordance with the theory of ambipolar diffusion transfer. Provided with different working air pressure, ion energy distribution exhibit different characteristics. High peak power pulse and low pulse duty factor (0.5%~10%) are applied during discharge process to achieve high ionization (>50%), which exhibited good adhesion, having overwhelming advantage in controlling coating structure and reducing internal stress of coating. From proceeding application status of preparing coatings using HPPMS technology, this work introduced characteristics and advantages of the high ionization rate physical vapor deposition coating, and research progress in hard coating preparation and coating interface optimization. Future development trend of high ionization rate physical vapor deposition coating was discussed, and application effect of the coatings was analyzed.

KEY WORDS: high ionization rate physical vapor deposition; film adhesion; coating characteristics; hard coating; peak power; ion energy

收稿日期: 2017-01-20; 修订日期: 2017-05-10

Received: 2017-01-20; Revised: 2017-05-10

作者简介: 钟厉 (1965—), 女, 博士, 教授, 主要研究方向为表面工程、先进制造技术。

Biography: ZHONG Li (1965—), Female, Doctor, Professor, Research focus: surface engineering, advanced manufacturing technology.

物理气相沉积技术广泛用来沉积光学涂层、磁性涂层、超硬涂层、热障涂层^[1]等具有特殊性能的涂层。然而一般物理气相沉积技术的金属离化率很低,且相当一部分金属都处于原子状态,导致很多涂层制备与应用受限。有关物理气相沉积技术的研究开发受到了国内外学者的广泛关注,其中有电子回旋共振磁控溅射 (ECR-MS)、空心阴极磁控溅射 (HCM)、高离化率物理气相沉积技术 (HPPMS)、电感耦合等离子体磁控溅射 (ICP-MS) 与自持放电磁控溅射等。其中,高离化率物理气相沉积技术离化率较高,使用低脉冲占空比与高脉冲峰值功率来溅射金属,从而使金属的离化率得到提高^[2-4]。高离化率物理气相沉积技术制备的涂层有很多优势,并且可以提高涂层的质量,对反应控制、形状复杂的工件以及定位沉积材料到不同区域等具有重要的影响。

1 高离化率物理气相沉积涂层的特点及研究现状

高离化率物理气相沉积技术能够产生等离子体,这些等离子体能量和离化率较高。Anders 等^[5-6]在 Thorton 结构区域模型基础上,研究出含有离子刻蚀与等离子体沉积的结构区域模型,将涂层结构与气压、温度之间的关系延伸至结构与离子能量之间的关系。涂层性能受离子分布和能量的影响,当离子能量较低时,能够沉积出柱状涂层与高致密度的纤维晶,而离子能量超过 10 eV 时,涂层的厚度会变小,等离子体沉积作用会加强。当离子能量不断增加到 10^3 eV 时,涂层的沉积作用明显小于离子的轰击作用,在沉积涂层的整个过程中,涂层厚度不再增加,基体表面出现负沉积,进而蚀刻基体表面组织。高离化率物理气相沉积技术还能对带电离子施加偏压,通过产生高能粒子轰击整个涂层。在离子轰击作用下,离子束流进入基体与涂层界面之间,使涂层局部外延生长,基体与涂层间的结合力会加强。在离子能量的影响下,涂层结构变紧凑,涂层表面颗粒变小,晶体的择优取向发生改变^[7-8]。

涂层生长过程中,在脉冲周期内会产生大量的流量离子流,这些离子流能够改变涂层表面的延伸能力,提高涂层表面的均匀性,增加涂层的密实度。生长过程中同时存在离子轰击作用,离子轰击能够促使再结晶与重复形核,控制涂层中的柱状晶晶粒贯穿性生长,改善涂层性能,使晶粒细化^[9]。例如,在沉积条件相同的情况下,用 HPPMS 技术与 MAIP 技术 (多弧离子镀) 分别沉积 CrN 涂层,对涂层结构进行对比发现, HPPMS 技术制备的涂层比较光滑与紧凑,柱状晶生长被限制,且一些晶粒在其他柱状晶上会二次形核生长。而 MAIP 技术沉积的涂层

柱状晶结构不致密,表面粗糙度较高^[10-15]。随着轰击作用的加强,离子能量和密度增加,涂层开始二次形核生长,且可以从致密的柱状晶向纳米晶转化。不同峰值脉冲下沉积的涂层组织结构 (图 1) 和形貌有所不同,用 HPPMS 技术沉积 CrN 涂层,当峰值电流达到 44 A 时,涂层的柱状结构非常紧密;当峰值电流加大到 74、180 A 时,晶粒细化,成为无宏观特征且表面平滑的纳米晶组织,此时沉积的 CrN 涂层为 (200) 晶体择优取向,与直流溅射中 (111) 择优取向相对应^[16-17]。

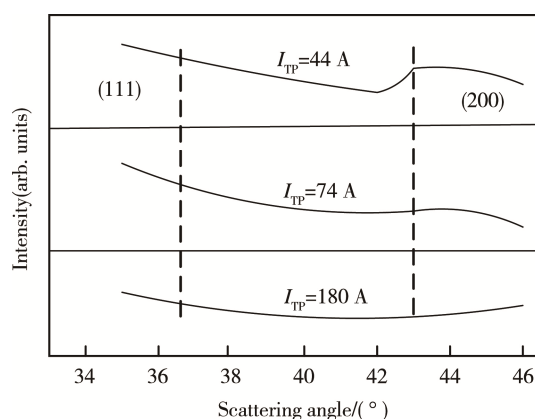


图 1 不同峰值脉冲时 HPPMS 技术沉积 CrN 涂层的 XRD 相结构^[18]

Fig.1 XRD phase structure of CrN coating deposited by HPPMS technique with different peak pulse

HPPMS 技术能够在低温下制得附着力强、耐腐蚀性好、摩擦系数低、硬度高的涂层,不但能够改变涂层的组织形态,还会影响涂层的结构。传统的物理气相沉积技术能在室温条件下沉积出高电阻率的亚稳 β -Ta 相,但是沉积出的涂层在低温条件下会发生结构变化,涂层厚度会降低^[19-24]。Alami 等^[25]采用 MPPMS 技术与 HPPMS 技术来沉积 Ta 涂层,通过对高离化率离子束的控制,在低温条件下沉积出了 α -Ta 相,涂层稳定性提高,且在低温、苛刻条件下,涂层结构不会发生改变。Bugaev 等^[26]采用 HPPMS 技术来沉积类金刚石碳膜,结果显示碳膜的 sp^3 键在 60%~70%之间,远远高于一般物理气相沉积金刚石碳膜中的 sp^3 键含量 (25%)。HPPMS 技术得到的金刚石碳膜表面的耐磨性能与硬度较高^[27]。对于结构复杂的化合物,其具有特殊的化学性质,且原子层的价键结构为 A—M 金属价键,具有很好的抗氧化性,因此化合物涂层在高温环境下的应用很有研究意义。Bobzin 等^[28]在 380 °C 条件下沉积 TiAlSiN 纳米复合涂层,涂层的韧性与硬度显著提高,在切削刀具上沉积 TiAlSiN 复合涂层,刀具使用寿命延长。

2 高离化率物理气相沉积涂层的技术优势

高离化率物理气相沉积技术能制备出高温、稳定、力学性能好、致密度高的涂层。如图 2 所示,采用直流溅射技术(DC)和 HPPMS 技术分别沉积 TiAlN 涂层, HPPMS-TiAlN 涂层的杨氏模量与硬度分别为 (377 ± 14) GPa 和 (34 ± 4) GPa, DC-TiAlN 涂层的杨氏模量与硬度分别为 (460 ± 19) GPa 和 (30 ± 1.5) GPa, 两种涂层的表面形貌所有不同, HPPMS-TiAlN 涂层的结构较致密且表面平整趋于光滑, DC-TiAlN 涂层的表面向外突起且凹凸不平^[29-30]。涂层韧性通过杨氏模量与硬度的比例调整,好的韧性体现在杨氏模量低和硬度较高, HPPMS-TiAlN 涂层有很好的韧性^[31]。将两种涂层通过 4 h、1000 °C 高温处理后, HPPMS-TiAlN 涂层晶体结构中出现 AlN 六方相,涂层的硬度提高,而 DC-TiAlN 涂层表面组织向外延伸,硬度有所下降。HPPMS-TiAlN 涂层与基体间具有较好的膜基结合力,而 DC-TiAlN 涂层表面有脱落现象。在抗高温氧化性能方面, HPPMS-TiAlN 涂层也远远优于一般的涂层,所以 HPPMS-TiAlN 涂层大量地运用于高速钢切削刀具^[32]。

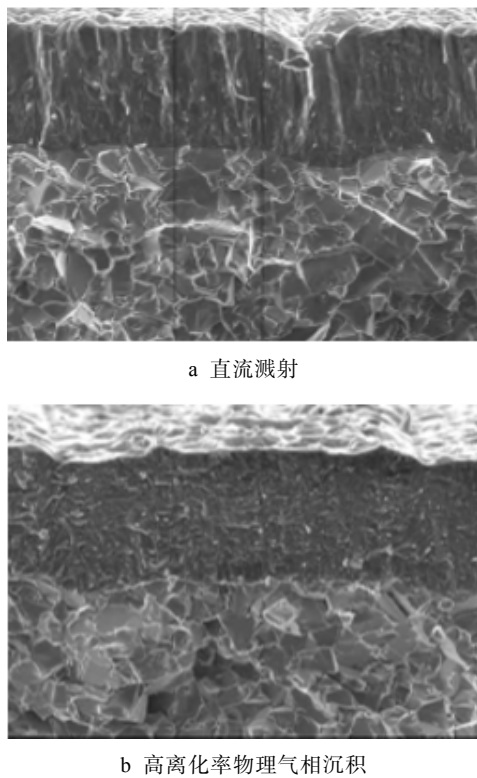


图 2 直流溅射和高离化率物理气相沉积 TiAlN 涂层的截面形貌对比^[33]
Fig.2 Cross section morphology contrast of DC sputtering (a) and high ionization rate physical vapor deposition (b) TiAlN coating

K. Bobzin 等人^[34]采用 MF、DC 与 HPPMS 沉积 (Ti,Si,Al)N 涂层。实验中采用正方形基体,其中一面和靶材所在面垂直,另一面和靶材平行。表 1 测出了沉积涂层在不同平面下的沉积速率。HPPMS 技术沉积涂层时,两平面的沉积速率差距非常小。MF 沉积涂层时,两平面的沉积速率比值上升。而用 DC 沉积涂层时,与靶平面垂直的平面的沉积速率低于与靶平面平行的平面的沉积速率。造成以上结果的原因是 HPPMS 有很高的离化率,在偏压的作用下,离子朝基体多方向沉积,从而保证了基体平面沉积的均匀性^[35-38]。

表 1 不同平面(Ti,Si,Al)N 沉积速率^[39]
Tab.1 Different plane (Ti, Si, Al)N deposition rate

Coating	Deposition rate (flank) / (nm·min ⁻¹)	Deposition rate (rake) / (nm·min ⁻¹)	Ratio (rake/flank)
DC (Ti,Si,Al)N	1.50	0.65	0.43
MF (Ti,Si,Al)N	1.35	0.8	0.59
HPPMS (Ti,Si,Al)N	1.46	1.05	0.72

HPPMS 技术具有高离化率,在偏压电场条件下,沉积粒子加速运动形成高能离子,可以对基体表面进行活化、轰击与清洗,以此增加基体与涂层之间的结合力。C. Reinhard 等^[40]沉积氮化铬超晶格涂层时,使用阴极弧清洗和预沉积 Nb 过渡层、HPPMS 清洗和预沉积 Nb 过渡层以及单独 HPPMS 清洗进行表面预处理。如图 3 所示,采用 HPPMS 处理的基体表面

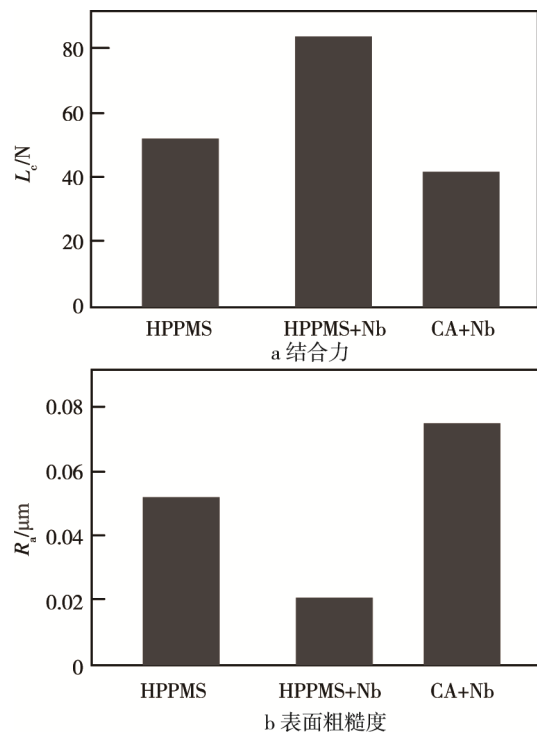


图 3 不同预处理方法沉积涂层的表面粗糙度与结合力^[44]
Fig.3 Surface roughness and binding force of deposition coatings by different pretreatment methods

在无过渡层的条件下,膜基结合力为 56 N。当加入 Nb 过渡层后,基体与涂层的结合力可达 85 N,并且 HPPMS 处理的涂层表面粗糙度远远低于阴极弧处理的涂层^[41—43]。采用阴极弧(CA)对基体进行处理,在沉积过渡层的条件下,涂层的临界载荷能达到 45 N,且阴极弧处理的基体表面粗糙度大于 HPPMS 处理的基体。

3 高离化率物理气相沉积涂层的发展趋势及应用效果分析

采用高离化率物理气相沉积涂层技术能够很大程度地加强基体的表面性能与灵活性, HPPMS 技术采用复合脉冲电源,利用这种电源能够沉积出膜基结合力好且表面金黄的涂层,且电源运行稳定可靠,沉积的涂层表面致密、清洁,其平均表面粗糙度很低,图 4 为脉冲波形。以 HPPMS 技术沉积 TiN 涂层为例, TiN 涂层的摩擦系数较低,耐磨性能较好,工艺范围非常广泛,即使是一般的靶材也能沉积出性能很好的涂层,图 5 为高速钢刀具表面沉积 TiN 涂层的摩擦磨损曲线^[45—46]。

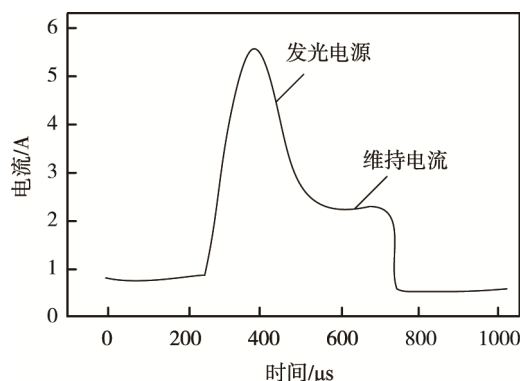


图 4 脉冲电流波形^[47]

Fig.4 Pulse current waveform

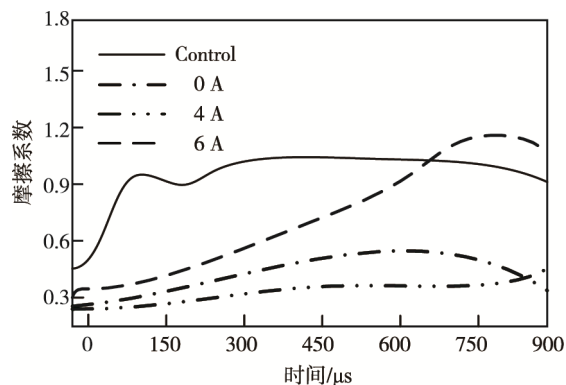


图 5 HPPMS 制备 TiN 涂层的摩擦磨损曲线^[48]

Fig.5 Friction and wear curve of TiN coating prepared by HPPMS

在沉积氧化物涂层方面,高离化率物理气相沉积技术有着巨大的发展潜力,沉积过程中, HPPMS

技术具有较好的控制性与离子轰击作用,在沉积透明导电膜等方面能够得到比较高的电导率与透过率。当沉积氧化钛、氧化铝等涂层时,能很好地控制化学计量比,沉积出来的涂层具有很好的耐磨性与耐腐蚀性^[49]。HPPMS 技术还可以用来沉积柔性聚合物涂层,采用 30 $\mu\text{m/h}$ 的沉积速率来制备铜优质碳膜,是一种非常具有研究意义的物理气相沉积方法。除此之外,国内外很多学者已经开始研究在等离子体上采用 HPPMS 技术来加强化学气相涂层(PECVD)的应用, PECVD 中的等离子体被高峰值功率密度与低占空比的脉冲引燃,等离子体化学活性很强,很容易发生反应,从而得到一种等离子体增强化学气相沉积方法,在 600 $^{\circ}\text{C}$ 的条件下沉积 $\alpha\text{-Al}_2\text{O}_3$ 相涂层,其力学性能远远优于传统的 CVD 工艺涂层^[50]。

4 结语

高离化率物理气相沉积技术是一种等离子体增强的物理气相沉积技术。它综合了膜基结合力强、无颗粒缺陷、表面光滑、金属离化率高等特点,沉积过程中原子发生高度离化。而且 HPPMS 技术在降低涂层内应力、控制涂层相结构等方面有很大的优势。国内外专家在不断的研究下取得了一定的学术成果,但是作为一种新型的物理气相沉积技术,还有很多地方不够完善,具体运用到工业实践中还有一定的难度。在低温沉积、刀具涂层界面的优化、高性能硬质涂层制备、复合高功率脉冲等方面都有待进一步提高,且沉积设备的稳定性还不够好,价格比较昂贵。但是随着研究工作的不断深入,高离化率物理气相沉积技术能够对机械产品性能的提升以及整个机械行业带来广阔的应用前景。

参考文献:

- [1] 牟仁德,王占考,陆峰,等. 力学载荷条件下 EB-PVD 热障涂层损伤行为研究[J]. 装备环境工程, 2016(3): 63—69.
MU Ren-de, WANG Zhan-kao, LU Feng, et al. Damage Behavior of Thermal Barrier Coatings Prepared by EB-PVD under Mechanical Load[J]. Equipment Environmental Engineering, 2016(3): 63—69.
- [2] STRANAK V, HERRENDORF A P, WULFF H, et al. Deposition of Rutile (TiO_2) with Preferred Orientation by Assisted High Power Impulse Magnetron Sputtering[J]. Surface and Coatings Technology, 2013, 222: 112—117.
- [3] 李春伟,苗红涛,徐淑艳,等. 复合高离化率物理气相沉积技术的研究进展[J]. 表面技术, 2016, 45(6): 82—90.
LI Chun-wei, MIAO Hong-tao, XU Shu-yan, et al. Composite Research Progress of High Power Pulsed Magnetron Sputtering Technology[J]. Journal of Surface Tech-

- nology, 2016, 45(6): 82—90.
- [4] STRANAK V, HERRENDORF A P, DRACHE S, et al. Highly Ionized Physical Vapor Deposition Plasma Source Working at Very Low Pressure[J]. *Applied Physics Letters*, 2012, 100(14): 141604.
 - [5] 陈海峰, 薛莹洁. 国内外磁控溅射靶材的研究进展[J]. *表面技术*, 2016, 45(10): 56—63.
CHEN Hai-feng, XUE Ying-jie, Domestic and Foreign Research Progress of Magnetron Sputtering Target Materials[J]. *Journal of Surface Technology*, 2016, 45(10): 56—63.
 - [6] KONSTANTINIDIS S, DAUCHOT J P, GANCIU M, et al. Transport of Ionized Metal Atoms in Highpower Pulsed Magnetron Discharges Assisted by Inductively Coupled Plasma[J]. *Applied Physics Letters*, 2006, 88(2): 021501.
 - [7] ZHANG Guo-jun, LIN Bin, JIANG Bai-ling, et al. Microstructure and Mechanical Properties of Multilayer Ti(C,N) Films by Closed-field Unbalanced Magnetron Sputtering Ion Plating[J]. *Journal of Materials Science & Technology*, 2010, 26(2): 119—124.
 - [8] WU Z, TIAN X, WEI Y, et al. Graded Nanostructured Interfacial Layers Fabricated by High Power Pulsed Magnetron Sputtering-plasma Immersion Ion Implantation and Deposition (HPPMS-PIII&D)[J]. *Surface and Coatings Technology*, 2013, 236: 320—325.
 - [9] WU Z, TIAN X, GONG C, et al. Micrograph and Structure of CrN Films Prepared by Plasma Immersion Ion Implantation and Deposition Using HPPMS Plasma Source[J]. *Surface and Coatings Technology*, 2013, 229: 210—216.
 - [10] 张臣, 黄美东, 陈泽昊, 等. 脉冲偏压对复合离子镀 (Ti,Cu)N 薄膜结构与性能的影响[J]. *表面技术*, 2015, 44(10): 22—26.
ZHANG Chen, HUANG Mei-dong, CHEN Ze-hao, et al. Effects of Pulsed Bias on the Structure and Properties of (Ti,Cu)N Coatings Prepared by Hybrid Ion Plating[J]. *Surface Technology*, 2015, 44(10): 22—26.
 - [11] OLEJNICEK J, HUBICKA Z, KMENT Š, et al. Investigation of Reactive HPPMS+MF Sputtering of TiO₂ Crystalline Thin Films[J]. *Surface and Coatings Technology*, 2013, 232: 376—383.
 - [12] KUSUMOTO Y, FURUTA H, SEKIYA K, et al. Electrical Conductance Behavior of Thin Ni Catalyst Films During Intermittent Direct Current Magnetron Sputtering[J]. *Journal of Vacuum Science & Technology A*, 2014, 32(3): 031502.
 - [13] HOLTZER N, ANTONIN O, MINEA T, et al. Improving HPPMS Deposition Rates by Hybrid RF/ HPPMS Co-sputtering, and Its Relevance for NbSi Films[J]. *Surface and Coatings Technology*, 2014, 250: 32—36.
 - [14] PANDIAN R, NATARAJAN G, RAJAGOPALAN S, et al. On the Phase Formation of Titanium Oxide Thin Films Deposited by Reactive DC Magnetron Sputtering: Influence of Oxygen Partial Pressure and Nitrogen Doping[J]. *Applied Physics A*, 2014, 116(4): 1—9.
 - [15] PAULITSCH J, SCHENKEL M, SCHINTLMEISTER A, et al. Low Friction CrN/TiN Multilayer Coatings Prepared by a Hybrid High Power Impulse Magnetron Sputtering/DC Magnetron Sputtering Deposition Technique[J]. *Thin Solid Films*, 2010, 518(19): 5553—5557.
 - [16] 毕明康. 磁场增强高功率脉冲磁控溅射放电特性及 TiAlN 涂层制备研究[D]. 哈尔滨: 哈尔滨工业大学, 2014: 17—45.
BI Ming-kang. Discharge Characteristics of Magnetic Field Enhanced High Power Impulse Magnetron Sputtering and Preparation of TiAlN Films[D]. Harbin: Harbin Institute of Technology, 2014: 17—45.
 - [17] GRECZNSKI G, LU J, JOHANSSON M, et al. Selection of Metal Ion Irradiation for Controlling Ti_{1-x}Al_xN Alloy Growth via Hybrid HPPMS/Magnetron Co-sputtering[J]. *Vacuum*, 2012, 86(8): 1036—1040.
 - [18] HOU S Q, DAI J J, SONG X, et al. Characteristic of TiN Film Prepared by Multiarc Ion Plating[J]. *Applied Mechanics and Materials*, 2014, 446: 254—258.
 - [19] POOLCHARUANSIN P, LIEBIG B, BRADLEY J. Plasma Parameters in a Preionized HPPMS Discharge Operating at Low Pressure[J]. *IEEE Transactions on Plasma Science*, 2010, 38(11): 3007—3015.
 - [20] SUN G D, YI D L, LIU C H. Comparison of Surface Properties of TiN and TiAlN Coating Prepared by Arc Ion Plating for the Improvement of Lifetime Extension of Tool Steel[J]. *Advanced Materials Research*, 2014, 887: 1096—1100.
 - [21] LUO Q, YANG S, COOKE K E. Hybrid HPPMS and DC Magnetron Sputtering Deposition of TiN Coatings: Deposition Rate, Structure and Tribological Properties[J]. *Surface and Coatings Technology*, 2013, 236: 13—21.
 - [22] OKS E, ANDERS A. Evolution of the Plasma Composition of a High Power Impulse Magnetron Sputtering System Studied with a Time-of-flight Spectrometer[J]. *J Appl Phys*, 2009, 105: 1—9.
 - [23] CHRISTIE D J. Target Material Pathways Model for HighPower Pulsed Magnetron Sputtering[J]. *Journal of Vacuum Science & Technology A*, 2005, 23(2): 330—335.
 - [24] AIEMPANAKIT M, HELMERSSON U, AIJAZ A, et al. Effect of Peak Power in Reactive High Power Impulse Magnetron Sputtering of Titanium Dioxide[J]. *Surface and Coatings Technology*, 2011, 205: 4828—4831.
 - [25] BRENNING N, HUO C, LUNDIN D, et al. Understanding Deposition Rate Loss in High Power Impulse Magnetron Sputtering: I. Ionization-driven Electric Fields[J]. *Plasma Sources Science and Technology*, 2012, 21: 025005.
 - [26] HOVSEPIAN P E, EHIASARIAN A P, RATAYSKI U. CrAlCN/CrCN Nanoscale Multilayer PVD Coatings Deposited by the Combined High Power Impulse Magnetron Sputtering/Unbalanced Magnetron Sputtering (HPPMS/UBM) Technology[J]. *Surface and Coatings Technology*, 2009, 203 (9): 1237—1243.
 - [27] MISHRA A, KELLY P J, BRADLEY J W. The Evolution of the Plasma Potential in a HPPMS Discharge and Its Relationship to Deposition Rate[J]. *Plasma Sources Science and Technology*, 2013, 22: 045012.
 - [28] BOBZIN K, BAGCIVAN N, IMMICH P, et al. Advantages of Nanocomposite Coatings Deposited by High

- Power Pulse Magnetron Sputtering Technology[J]. J Mater Process Technol, 2008, 209: 165—170.
- [29] LAZAR J, VLEK J, REZEK J. Ion Flux Characteristics and Efficiency of the Deposition Processes in High Power Impulse Magnetron Sputtering of Zirconium[J]. Journal of Applied Physics, 2010, 108: 063307.
- [30] ANDERS A. Discharge Physics of High Power Impulse Magnetron Sputtering[J]. Surface and Coatings Technology, 2011, 205(S2): S1—S1.
- [31] EMMERLICH J, STANISLAY M, SNYDERS R, et al. The Physical Reason for the Apparently Low Deposition Rate During Highpower Pulsed Magnetron Sputtering[J]. Vacuum, 2008, 82: 867—870.
- [32] ANDERS A. A Review Comparing Cathodic Arcs and High Power Impulse Magnetron Sputtering (HPPMS)[J]. Surface and Coatings Technology, 2014, 257: 308—325.
- [33] MISHRA A, KELLY P J, BRADLEY J W. The Evolution of the Plasma Potential in a HPPMS Discharge and Its Relationship to Deposition Rate[J]. Plasma Sources Science and Technology, 2010, 19: 045014.
- [34] SAMUELSSON M, LUNDIN D, JENSEN J, et al. On the Film Density Using High Power Impulse Magnetron Sputtering[J]. Surface and Coatings Technology, 2010, 205(2): 591—596.
- [35] KONSTANTINIDIS S, DAUCHOT J P, GANCIU M, et al. Influence of Pulse Duration on the Plasma Characteristics in Highpower Pulsed Magnetron Discharges[J]. Journal of Applied Physics, 2006, 99(1): 013307.
- [36] SAMUELSSON M, SARA KINOS K, HOGBERG H, et al. Growth of Ti-C Nanocomposite Films by Reactive High Power Impulse Magnetron Sputtering under Industrial Conditions[J]. Surface and Coatings Technology, 2012, 206(8): 2396—2402.
- [37] HELMERSSON U, LATTEMANN M, BOHLMARK J, et al. Ionized Physical Vapor Deposition (IPVD): A Review of Technology and Applications[J]. Thin Solid Films, 2006, 513(1): 1—24.
- [38] REED A N, LANGE M A, MURATORE C, et al. Pressure Effects on HPPMS Deposition of Hafnium Films[J]. Surface and Coatings Technology, 2012, 206(18): 3795—3802.
- [39] BOBZIN K, BAGCIVAN N, IMMICH P, et al. Advantages of Nanocomposite Coatings Deposited by High Power Pulse Magnetron Sputtering Technology[J]. Journal of Materials Processing Technology, 2009, 209(1): 165—170.
- [40] CHOI J, SOEJIMA K, KATO T, et al. Nitriding of High Speed Steel by Bipolar PBII for Improvement in Adhesion Strength of DLC Films[J]. Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 2012, 272: 357—360.
- [41] 吴忠振, 朱宗涛, 巩春志, 等. 高离化率物理气相沉积技术的发展与研究[J]. 真空, 2009, 46(3): 18—22.
- WU Zhong-zhen, ZHU Zong-tao, GONG Chun-zhi, et al. Development of High-power Pulse Magnetron Sputtering Technology[J]. Vacuum, 2009, 46(3): 18—22.
- [42] EHIASARIAN A P, WEN J G, PETROV I. Interface Microstructure Engineering by High Power Impulse Magnetron sputtering for the Enhancement of Adhesion[J]. Journal of Applied Physics, 2007, 101: 054301.
- [43] 马永乐. 高功率调制脉冲磁控溅射沉积纳米 Cu 涂层工艺研究[D]. 大连: 大连交通大学, 2012: 44—50.
- MA Yong-le. Experimental Investigation of Nano Copper Deposition Film by Modulated Pulsed Power Magnetron Sputtering[D]. Dalian: Dalian Jiaotong University, 2012: 44—50.
- [44] LIN J L, JOHN J M, WILLIAM D S, et al. Modulated Pulse Power Sputtered Chromium Coatings[J]. Thin Solid Films, 2009, 518: 1566—1570.
- [45] 吴志立, 朱小鹏, 雷明凯. 高功率脉冲磁控溅射沉积原理与工艺研究进展[J]. 中国表面工程, 2012, 25(5): 15—20.
- WU Zhi-li, ZHU Xiao-peng, LEI Ming-kai. Progress in Deposition Principle and Progress Characteristics of High Power Pulse Magnetron Sputtering[J]. China Surface Engineering, 2012, 25(5): 15—20.
- [46] HOVSEPIAN P E, REINHARD C, EHIASARIAN A P. CrAlYN/CrN Superlattice Coatings Deposited by the Combined High Power Impulse Magnetron Sputtering/Unbalanced Magnetron Sputtering Technique[J]. Surface and Coatings Technology, 2006, 201(7): 4105—4110.
- [47] 牟晓东. 高功率脉冲非平衡磁控溅射法制备 CrN_x 膜和 Cu 膜及其沉积特性的研究[D]. 大连: 大连理工大学, 2011: 22—25.
- MU Xiao-dong. Study of the Deposition and Properties of CrN_x and Cu Films by High Power Pulsed Unbalanced Magnetron Sputtering[D]. Dalian: Dalian Ligong University, 2011: 22—25.
- [48] 李春伟, 田修波, 巩春志, 等. 不同氩气压下钨靶 HPPMS 放电特性的演变[J]. 表面技术, 2016, 45(8): 103—109.
- LI Chun-wei, TIAN Xiu-bo, GONG Chun-zhi, et al. Vanadium Target Under Different Argon Pressure HPPMS the Evolution of the Discharge Characteristics[J]. Journal of Surface Technology, 2016, 45(8): 103—109.
- [49] LATTEMANN M, EHIASARIAN A P, BOHLMARK J, et al. Investigation of High Power Impulse Magnetron Sputtering Pretreated Interfaces for Adhesion Enhancement of Hard Coatings on Steel[J]. Surface and Coatings Technology, 2006, 200(22): 6495—6499.
- [50] REINHARD C, EHIASARIAN A P, HOVSEPIAN P E. CrN/NbN Superlattice Structured Coatings with Enhanced Corrosion Resistance Achieved by High Power Impulse Magnetron Sputtering Interface Pretreatment[J]. Thin Solid Films, 2007, 515(7): 3685—3692.