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有机硅/改性纳米TiO₂/石蜡基复合缓蚀剂的制备及其性能

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摘要: 为改善高能发射药R2的烧蚀性,设计制备了一种有机硅/改性纳米TiO₂/石蜡基新型复合缓蚀剂,利用半密闭爆发器试验,以制式缓蚀剂为参比物,测试了新型复合缓蚀剂的降烧蚀性能,并利用扫描电子显微镜结合能谱仪(SEM-EDS)研究了缓蚀机理,采用密闭爆发器研究新型复合缓蚀剂对发射药静态燃烧性能的影响。结果表明:新型复合缓蚀剂降烧蚀效果显著,添加5%时,缓蚀率可达34.24%;缓蚀剂中的十甲基环五硅氧烷(D5)在高温下分解,产生的硅氧化物纳米小球附着于烧蚀管内壁,能有效阻碍渗碳反应的发生;加入新型复合缓蚀剂的R2发射药燃烧渐增性增强,能量集中于燃烧后期释放,利于改善烧蚀。该新型复合缓蚀剂有巨大的应用潜力。

关键词: 降烧蚀;有机硅缓蚀剂;高能发射药;复合材料

中图分类号: TJ55;TQ562

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0 引言

发射药在火炮内膛燃烧后,形成的高温、高压、高速燃气将弹丸由身管中发射^[1]。在这一过程中,身管因内膛表面受到火药燃气的传热与冲刷,弹丸和弹带的摩擦而受到烧蚀磨损,火炮的精度、射程和弹丸初速降低,寿命缩短^[2-4]。国内外研究认为热-化学-机械三者的复合作用影响烧蚀^[5-7],CO₂、CO、H₂、N₂等发射药燃气在高温、高压环境下与身管炮钢材料发生渗碳、渗氮、氧化等化学反应,生成FeC、FeC₃、FeN、FeO等低熔点产物^[8-10],在热作用下局部出现熔化现象,使得内膛表面机械强度降低、脆性增加,更容易在气流冲刷、弹带摩擦等机械作用下形成裂纹、剥落^[11-12],增加暴露在燃气中的面积,加速化学反应,同时,身管随着冷热循环反复膨胀与收缩而产生的内应力也会加剧裂纹扩展^[13-14],导致裂纹不断增多、加深直至形成裂纹网。

为解决身管烧蚀问题,科研工作者提出了一些可

行的方法,包括改进发射药配方^[15-17]、改善身管材料和内膛镀层^[18-20]、身管自修复技术^[21]及缓蚀添加剂技术^[22-24]等,其中缓蚀添加剂技术(简称缓蚀剂)简单高效易行,能有效降低烧蚀磨损,提高火炮寿命。

缓蚀剂通常由二氧化钛(TiO₂)、滑石粉、二氧化硅等无机化合物与石蜡、地蜡、聚氨酯等有机化合物组成^[25-27],在身管武器运用广泛,为提升降烧蚀性能,目前开发了有机硅^[28-29]、脲醛树脂复合物^[30-31]、MoS₂复合物^[32]、稀土氧化物^[33]等缓蚀剂。这些缓蚀剂虽然能够满足大威力火炮的基本降烧蚀要求,但是普遍存在缓蚀效率偏低和降低内弹道性能等问题,随着发射药向高能量、高装填密度发展,制式缓蚀剂难以满足火炮的降烧蚀要求。

R2发射药是近年来重点研发的一种高能量密度发射药,具有爆温高、爆热大等特点。R2发射药的应用使身管内膛温度和压力增高,已有的制式缓蚀剂难以有效地降低烧蚀,导致工作环境更恶劣。为此,本研究针对R2高能发射药,设计了一种D5/改性纳米TiO₂/石蜡新型缓蚀材料,并采用半密闭爆发器烧蚀实验和扫描电子显微镜结合能谱仪对其降烧蚀性能和缓蚀机理进行研究,通过密闭爆发器就新型复合缓蚀剂对发射药静态燃烧性能的影响也进行了研究,为高效缓蚀剂设计提供了新思路。

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1 实验部分

1.1 原材料与仪器

原材料:R2高能硝胺发射药,辽宁庆阳特种化工有限公司;聚乙二醇400,平均分子量400,上海阿拉丁生化科技股份有限公司;无水乙醇,99.8%,国药集团化学试剂有限公司;3-氨丙基三乙氧基硅烷(KH-550),99%,上海阿拉丁生化科技股份有限公司;石蜡,58~60℃,国药集团化学试剂有限公司;D5,99%,国药集团化学试剂有限公司;TiO₂,99%,≤100 nm,上海阿拉丁生化科技股份有限公司。

仪器:电子天平,DH-30,南京精久电子衡器有限公司;防爆水浴烘箱,AHX871,南京理工大学机电厂;超声波分散仪,KQ3200DE,江苏昆山市超声仪器有限公司;配备能量色散X射线光谱(EDS)的场发射扫描电子显微镜(SEM),Quanta 250,美国FEI公司;密闭爆发器,泸州北方化学工业有限公司。

1.2 发射药的制备及材料改性

R2高能硝胺发射药,药型为25/19H,长径比1.1,采用半溶剂挤压成型工艺制得。过程为:称取0.2 g聚乙二醇置于100 mL无水乙醇中,搅拌均匀后,再加入5 g纳米TiO₂,继续搅拌10 min,在温度60℃,功率200 W条件下超声15 min,得到纳米TiO₂分散液;将1.5 mL KH-550置于50 mL乙醇、水混合溶液(体积比为1:1),搅拌5 min后得到KH-550乙醇水溶液;将KH-550乙醇水溶液逐滴加入到纳米TiO₂分散液中,滴加完成后,在60℃下继续搅拌1.5 h,转速为500 r·min⁻¹;反应结束后,进行真空抽滤,用乙醇洗涤三次以上,所得固体放入50℃烘箱干燥48 h,即得到KH-550改性TiO₂,命名为K-Ts。

1.3 缓蚀剂配方及制备

以D5、K-Ts和石蜡为主要组分设计了4种不同组分新型复合缓蚀剂,配方及名称如表1所示。制备流程如下:首先按份额称量石蜡、K-Ts和D5;其次调节水浴温度为60℃,将石蜡加入烧瓶先行熔化,依次加入K-Ts和D5,开启超声预混;随后搅拌,转速为400 r·min⁻¹,搅拌1 h。混合结束,待样品冷却固化,取出切割成粉末状备用。为进行降烧蚀性能对比研究,本研究同时制备了制式缓蚀剂,样品命名为HS-R。

1.4 半密闭爆发器烧蚀实验

采用烧蚀管质量损失法,称量烧蚀前后烧蚀管的质量,通过两者的质量差分析新型复合缓蚀剂的降烧

表1 新型复合缓蚀剂的配方组成

Table 1 Formulation of new composite erosion inhibitor %

sample	C _{Paraffin}	C _{D5}	C _{K-Ts}
HS-1	50	15	35
HS-2	50	35	15
HS-3	70	15	15
HS-4	50	25	25

Note: C_{Paraffin} is the mass percentage of paraffin in the new composite erosion inhibitor, C_{D5} is the mass percentage of D5 in the new composite erosion inhibitor, and C_{K-Ts} is the mass percentage of K-Ts in the new composite erosion inhibitor.

蚀性能。实验选用烧蚀管材料为45#钢,发射药装填密度为0.2 g·cm⁻³;常温下每个烧蚀管测量3次;实验点火选用3#NC,药量1 g。为测试新型复合缓蚀剂配方对降烧蚀性能的影响,分别添加了3% HS-R、3% HS-1、3% HS-2、3% HS-3、3% HS-4缓蚀剂。为测试新型复合缓蚀剂添加量对降烧蚀性能的影响,分别添加了1%、3%、5% HS-2缓蚀剂。缓蚀剂装填方式是将缓蚀剂用同样大小的药包纸包裹,并置于发射药前端。

试验后,首先使用丙酮清洗烧蚀管,再用乙醇清洗烧蚀管,完全烘干后,冷却至室温再进行检测。对烧蚀管进行切割,烧蚀管按无缓蚀剂、3% HS-1、3% HS-2、3% HS-3、3% HS-4、3% HS-R、1% HS-2、5% HS-2的顺序进行编号,样品分别命名为S1~S8,随后用扫描电子显微镜结合能谱仪(SEM-EDS)对其内壁多个区域进行了随机测试。

1.5 静态定容燃烧实验

利用密闭爆发器实验,通过压电传感器监测有无缓蚀剂的R2发射药的燃烧过程的压力变化,分析不同缓蚀剂对R2发射药静态燃烧性能的影响。实验用发射药装填密度为0.2 g·cm⁻³;常温对每个发射药样品各测量1次;实验点火选用3#NC,药量1 g。为测试新型复合缓蚀剂对R2发射药静态燃烧性能的影响,分别添加了3%HS-R、3% HS-1、3% HS-2、3% HS-3、3% HS-4缓蚀剂;缓蚀剂装填方式采用将缓蚀剂用同样大小的药包纸包裹,并置于发射药前端。

2 结果与讨论

2.1 新型复合缓蚀剂降烧蚀性能

以HS-R为参比物,测试新型复合缓蚀剂配方和添加量对降烧蚀性能的影响,根据烧蚀管质量损失对比自制缓蚀剂的降烧蚀性能,实验结果如表2所示。

表2 添加不同缓蚀剂时R2发射药的烧蚀实验结果

Table 2 Erosion test results of R2 propellant with different erosion inhibitors

NO	inhibitor	w / %	p_m / MPa	E / g	E_n / %
S1	None	0	256	1.9536	—
S2	HS-1	3	265	1.6033	17.93
S3	HS-2	3	262	1.4764	24.43
S4	HS-3	3	263	1.5142	22.49
S5	HS-4	3	264	1.5209	22.15
S6	HS-R	3	264	1.7664	9.58
S7	HS-2	1	266	1.6920	13.40
S8	HS-2	5	268	1.2848	34.24

Note: w is the amount of added erosion inhibitor, p_m is the maximum pressure, E is the mass loss of the erosion tube and E_n is the erosion inhibition rate.

由表2可见,添加缓蚀剂的发射药烧蚀率显著降低,当添加量为3%时,HS-1~HS-4缓蚀剂的缓蚀率分别为17.93%、24.43%、22.49%和22.15%,而HS-R缓蚀剂的缓蚀率则只有9.58%,这表明新型复合缓蚀剂降烧蚀效果显著优于制式缓蚀剂。随配方中D5含量提高,烧蚀管质量损失减少,新型复合缓蚀剂的缓蚀率增加,经分析认为,这可能由于D5在高温下更易吸热分解,可以大幅降低烧蚀管内温度,从而降低R2发射药的烧蚀性。此外,HS-2缓蚀剂的添加量增加至5%时,缓蚀率可达34.24%。

利用扫描电镜观察烧蚀过后的烧蚀管内壁微观形貌,结果如图1所示。由图1可以看出,S1~S6表面整体平滑,由放大图像可清晰观察到烧蚀管表面存在沿晶粒方向延伸而形成的网状裂纹,这是表面金属快速热膨胀和冷收缩形成的应力开裂。与S2~S5相比,S1和S6表面裂纹更为密集,裂缝的宽度与深度均大于前者,分析认为新型复合缓蚀剂通过降低火药气体的热传递,使得烧蚀管表面温度波动降低,减少裂纹的产生,从而达到改善烧蚀的效果。

2.2 烧蚀管内壁表面分析

通过能谱仪对烧蚀过后的烧蚀管内壁表面元素组成进行分析,结果见表3。从表3可以看出,S1和S6表面C元素含量分别为7.8%和12.3%,表面组织结构松散,可知其表面发生了渗碳反应。而S2~S5表面多处均只检测到痕量C元素含量,如果存在渗碳反应,烧蚀管表面碳元素含量应远超过该量,因此分析认为添加新型复合缓蚀剂的烧蚀管表面不存在渗碳反应,这是由于新型复合缓蚀剂吸热分解产生的附着层能够有效阻碍渗碳反应的进行。

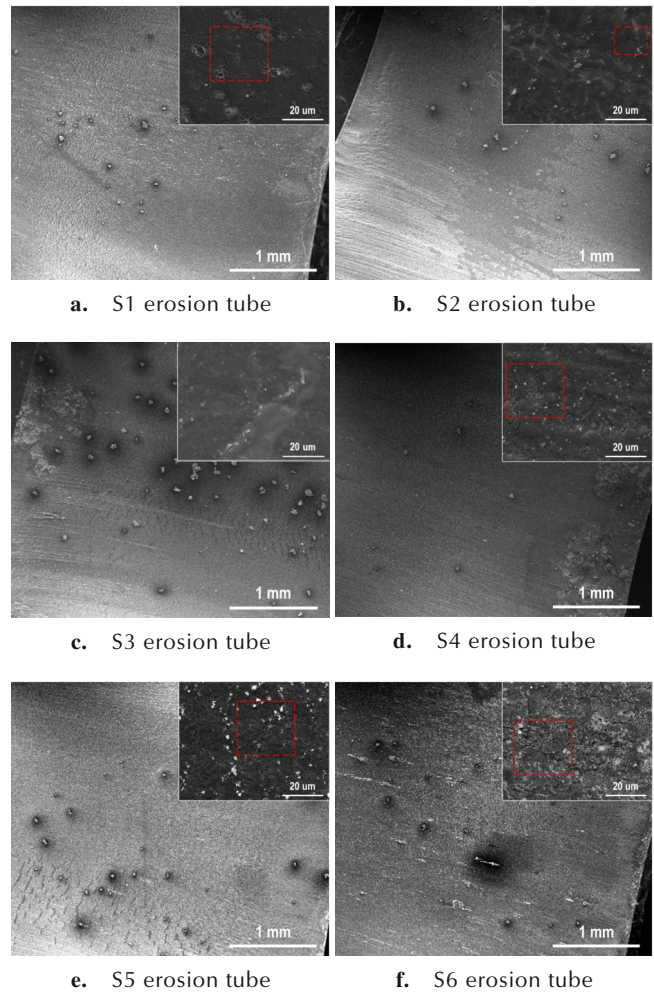


图1 S1~S6烧蚀管内壁表面SEM图像

Fig.1 SEM images of the inner wall surface of S1~S6 erosion tube

表3 烧蚀管内壁表面元素组成

Table 3 Element composition of inner wall surface of erosion tube

No.	C	O	Si	Fe	Ti
S1	7.84	23.27	4.32	57.73	—
S2	—	22.39	3.20	66.55	—
S3	—	27.10	5.88	60.69	0.81
S4	—	27.03	3.57	63.30	—
S5	—	16.48	4.80	78.72	—
S6	12.39	23.05	3.04	57.66	2.28

为了确定烧蚀管表面附着物的成分,对其表面进行了元素分布扫描,得到元素分布图,如图2所示。由图2a~2d可以看出,在S2~S5表面的附着物主要是纳米级的颗粒状小球,而Si和O元素则主要集中于此区域。分析认为这是在火药燃烧过程中D5吸热分解产生的硅氧化物小颗粒。在S6表面则检测到Ti元素,附

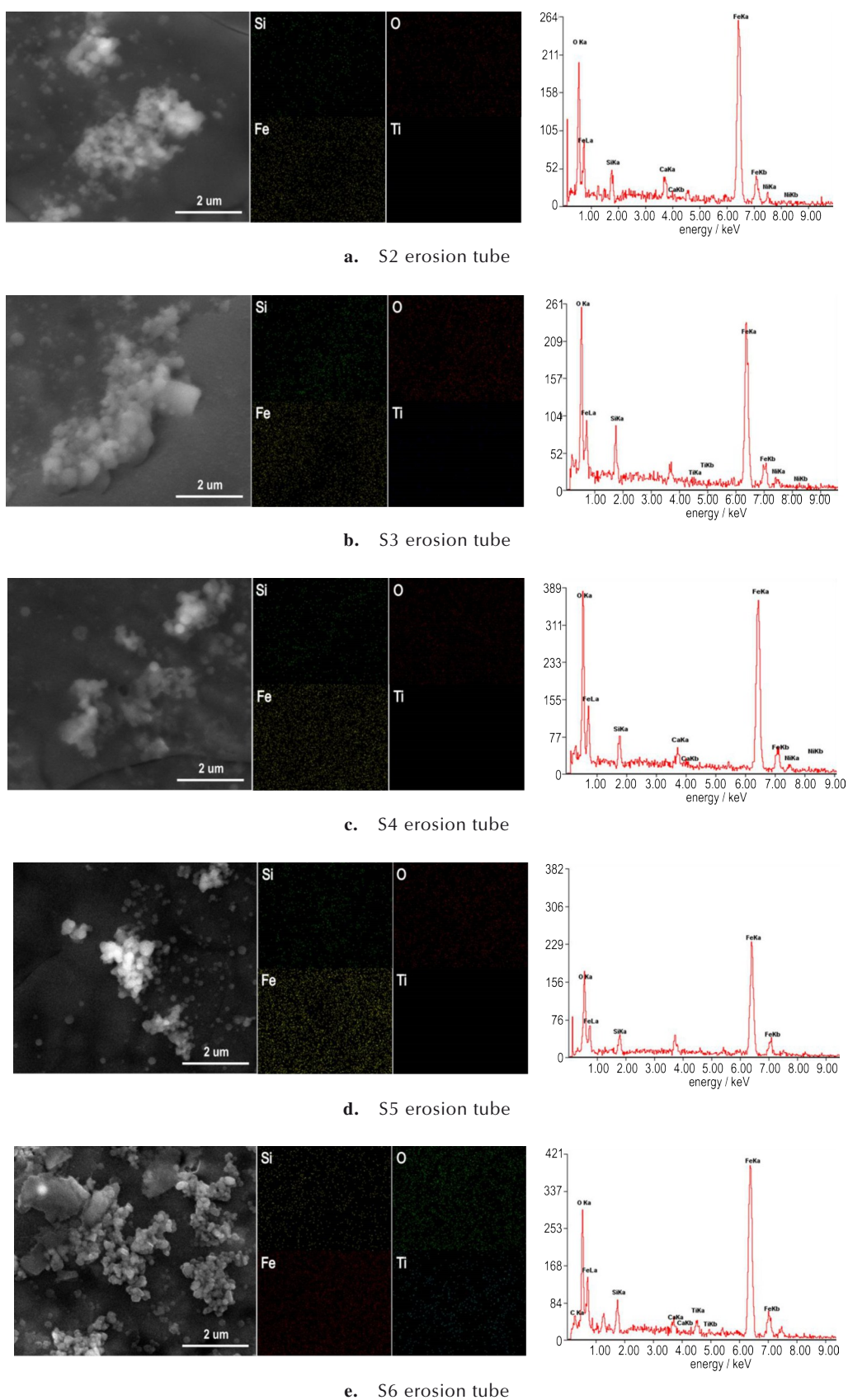


图2 S2~S6烧蚀管内壁SEM照片及元素分布

Fig.2 SEM photos and elemental distribution on the inner wall surface of S2~S6 erosion tube

着物颗粒处主要分布Ti、Si和O元素(图2e),这表明Ti和Si元素主要是滑石粉和二氧化钛经过烧蚀后剩余的残留物。综上可知,新型复合缓蚀剂的降烧蚀机理主要是:一是石蜡和D5在高温下吸热分解,降低火药气体的燃烧温度,从而改善发射药的烧蚀性;二是D5分解产生的纳米级硅氧化物小球有效附着于烧蚀管内壁,形成保护层,可以阻碍火药气体与烧蚀管表面基体发生反应;三是硅氧化物小球具有更低的导热率,可以降低火药气体对于烧蚀管内壁的热传递,从而降低烧蚀量。

2.3 新型复合缓蚀剂对发射药静态燃烧性能的影响

采用密闭爆发研究无缓蚀剂、添加新型复合缓蚀剂以及添加制式缓蚀剂对R2发射药静态燃烧性能的影响,得到了 $p-t$ 曲线和 $L-B$ 曲线。从图3a中可以看出,缓蚀剂的加入使得R2发射药燃烧时间增加了0.5~1 ms左右, p_m 提升了5~10 MPa,这是由于石蜡和D5在50~140 °C吸热相变延缓了火药前期的压力上升速率,中后期分解形成还原性物质所致。由图3b可知,当 B 小于0.6时,加入缓蚀剂的发射药 L 略低于R2

发射药;当 B 大于0.6时, L 开始下降,此时加入缓蚀剂的发射药 L 下降速度慢于R2发射药,说明新型复合缓蚀剂的加入增强了R2发射药的燃烧渐增性。这使发射药的能量更加集中于在燃烧后期释放,有效改善烧蚀现象,有利于改善装药内弹道性能。

3 结论

(1)通过半密闭爆发器烧蚀实验可证,新型复合缓蚀剂具有良好的降烧蚀性能,缓蚀效果显著优于制式缓蚀剂。

(2)随配方中D5比例提高,新型复合缓蚀剂的缓蚀率增加,在HS-2缓蚀剂添加量为5%时,缓蚀率高达34.24%。

(3)由密闭爆发器实验可知,新型复合缓蚀剂的加入增强了R2发射药的燃烧渐增性,使得能量更加集中于在燃烧后期释放,有利于改善装药内弹道性能。

参考文献:

- [1] 王泽山, 何卫东, 徐复铭. 火药装药设计原理与技术[M]. 北京: 北京理工大学出版社, 2014: 73-90.
WANG Ze-shan, HE Wei-dong, XU Fu-ming. Design principles and techniques of gunpowder charge[M]. Beijing: Beijing Institute of Technology Press, 2014: 73-90.
- [2] 张喜发, 卢兴华. 火炮烧蚀内弹道学[M]. 北京: 国防工业出版社, 2001: 1-20.
ZHANG Xi-fa, LU Xing-hua. Interior ballistics of gun erosion[M]. Beijing: National Defense Industry Press, 2001: 1-20.
- [3] 黄进峰, 张津, 陈俊宇, 等. 火炮身管失效机理与炮钢的发展[J]. 火炮发射与控制学报, 2023, 44(1): 10-29.
HUANG Jin-feng, ZHANG Jin, CHEN Jun-yu, et al. Failure mechanisms of gun barrels and the development of gun steel[J]. *Journal of Gun Launch & Control*, 2023, 44(1): 10-29.
- [4] 许耀峰, 杨雕, 刘朋科, 等. 火炮身管内膛表面材料强度退化机理研究[J]. 兵工学报, 2023, 44(5): 1288-1295.
XU Yao-feng, YANG Diao, LIU Peng-ke, et al. Study on strength degradation mechanism of material on inner bore surface of gun barrel[J]. *Acta Armamentarii*, 2023, 44(5): 1288-1295.
- [5] KUMAR D, KALRA S, JHA M. A concise review on degradation of gun barrels and its health monitoring techniques[J]. *Engineering Failure Analysis*, 2022, 142: 106791.
- [6] LI X, ZANG Y, MU L, et al. Erosion analysis of machine gun barrel and lifespan prediction under typical shooting conditions[J]. *Wear*, 2020, 444: 203177.
- [7] 韦丁, 王琼林, 严文荣, 等. 降低身管烧蚀性研究进展[J]. 火炸药学报, 2020, 43(4): 351-361.
WEI Ding, WANG Qiong-lin, YAN Wen-rong, et al. Research progress on reducing erosivity of gun barrel[J]. *Chinese Journal of Explosives & Propellants*, 2020, 43(4): 351-361.
- [8] 付佳维, 李延泽, 陈诗雨, 等. 大口径火炮身管损伤机理及寿命提升方法综述[J]. 装备环境工程, 2022, 19(7): 10-17.
FU Jia-wei, LI Yan-ze, CHEN Shi-yu, et al. Erosion mecha-

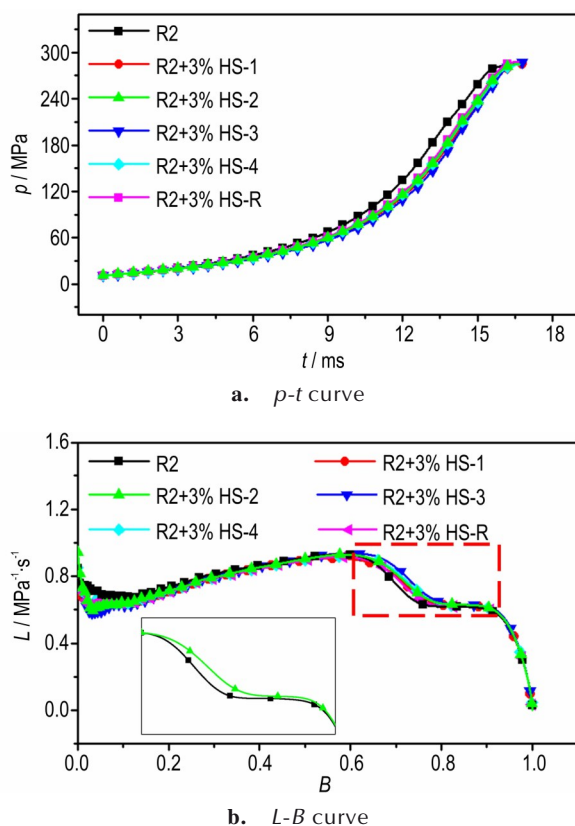


图3 不同缓蚀剂条件下R2发射药的静态燃烧性

Fig.3 Static combustion performance of R2 propellant with different inhibitors

- nisms and life improvement techniques of large calibre gun barrel [J]. *Equipment Environmental Engineering*, 2022, 19(7): 10-17.
- [9] 毛保全, 赵其进, 白向华, 等. 火炮身管延寿技术研究现状与展望[J]. 兵工学报, 2023, 44(3): 638-655.
MAO Bao-guan, ZHAO Qi-jin, BAI Xiang-hua, et al. Review and prospect of life extension technology for gun barrels [J]. *Acta Armamentarii*, 2023, 44(3): 638-655.
- [10] 张金, 赵亮, 王鑫, 等. 火炮身管内膛损伤机理分析[J]. 火力与指挥控制, 2020, 45(5): 8-14.
ZHANG Jin, ZHAO Liang, WANG Xin, et al. Mechanism analysis of internal defects in barrels [J]. *Fire Control & Command Control*, 2020, 45(5): 8-14.
- [11] 窦彩虹, 靳鹏飞, 陈俊宇, 等. 大口径机枪枪管内膛烧蚀行为与微观机理[J]. 兵工学报, 2022, 43(9): 2231-2240.
DOU Cai-hong, JIN Peng-fei, CHEN Jun-yu, et al. Ablation behavior and microscopic mechanism of large-caliber machine gun barrel [J]. *Acta Armamentarii*, 2022, 43(9): 2231-2240.
- [12] 张雯浩, 余永刚. 基于流固耦合的燃气冲刷烧蚀内膛特性分析[J]. 爆炸与冲击, 2023, 43(3): 138-148.
ZHANG Wen-hao, YU Yong-gang. Analysis of gas-eroding barrel characteristics based on fluid-solid interaction [J]. *Explosion and Shock Waves*, 2023, 43(3): 138-148.
- [13] 朱梦然, 曹京华, 先赫, 等. 身管内表面烧蚀磨损研究进展[J]. 兵器装备工程学报, 2023, 44(10): 159-164.
ZHU Meng-ran, CAO Jing-hua, XIAN He, et al. Research progress of erosion on inner bore surface of gun barrel [J]. *Journal of Ordnance Equipment Engineering*, 2023, 44(10): 159-164.
- [14] 李小龙. 速射武器身管材料劣化行为与弹道性能退化机理研究 [D]. 北京: 北京科技大学, 2021.
LI Xiao-long. Research on the deterioration behavior of the barrel material of the rapid-fire weapon and the degradation mechanism of ballistic performance. Beijing: University of Science and Technology Beijing, 2021.
- [15] LAVOIE J, PETRE C-F, DURAND S, et al. Stability and performance of gun propellants incorporating 3, 6-dihydrazino-s-tetrazine and 5-aminotetrazolium nitrate [J]. *Journal of Hazardous Materials*, 2019, 363: 457-463.
- [16] PADHAN M, MARATHE U, BIJWE J. A comparative assessment of nano and microparticles of carbides for performance augmentation of UHMWPE in abrasive and erosive wear modes [J]. *Wear*, 2023, 514: 204568.
- [17] 刘波, 王琼林, 刘少武, 等. 一种低烧蚀高渐增性发射药的研究 [J]. 含能材料, 2011, 19(5): 565-568.
LIU Bo, WANG Qiong-lin, LIU Shao-wu, et al. A study of propellant with low erosion and high combustion progressivity [J]. *Chinese Journal of Energetic Materials (Hanneng Cailiao)*, 2011, 19(5): 565-568.
- [18] HU M, SHEN M, LIU Z, et al. Self-ion bombarded Cr films: Crystallographic orientation and oxidation behavior [J]. *Corrosion Science*, 2018, 143: 212-220.
- [19] 谭继宇, 张效天, 张魏友, 等. 基于复合材料纤维缠绕增强技术的身管减重设计 [J]. 兵器装备工程学报, 2021, 42(1): 50-54.
TAN Ji-yu, ZHANG Xiao-tian, ZHANG Wei-you, et al. Barrel lightweight design based on filament winding strengthening technology of composite [J]. *Journal of Ordnance Equipment Engineering*, 2021, 42(1): 50-54.
- [20] 郭策安, 周峰, 胡明, 等. CrNi3MoVA 钢表面磁控溅射 Ta 涂层的摩擦磨损性能 [J]. 材料导报, 2018, 32(18): 3213-3216.
GUO Ce-an, ZHOU Feng, Hu Ming, et al. Performance of friction and wear of magnetron sputtered Ta coating on CrNi3MoVA steel [J]. *Materials Reports*, 2018, 32(18): 3213-3216.
- [21] 魏化震, 高守臻, 李大勇, 等. 延寿修复材料在身管武器上的应用研究 [J]. 兵工学报, 2017, 38(3): 440-446.
WEI Hua-zhen, GAO Shou-zhen, LI Da-yong, et al. Applied research on the life prolonged and restored materials in gun tube weapon [J]. *Acta Armamentarii*, 2017, 38(3): 440-446.
- [22] SUN N, XIAO Z. Effects of an organic-inorganic nanocomposite additive on the combustion and erosion performance of high energy propellants containing RDX [J]. *Propellants, Explosives, Pyrotechnics*, 2017, 42(11): 1252-1260.
- [23] WANG Y, DU K, LIU B, et al. Design and characterization of novel flexible phase change composite materials as protective liners for the cartridge case [J]. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 2024, 684: 133254.
- [24] FAN W, GAO P. A review on erosion-reducing additive materials to extend the lifespan of gun barrels [J]. *Journal of Materials Science*, 2021, 56(36): 19767-19790.
- [25] 徐鸿雷, 张健, 姜华, 等. 减小火炮内膛烧蚀和磨损的有效方法 [J]. 国防制造技术, 2018(01): 44-46.
XU Hong-lei, ZHANG Jian, JIANG Hua, et al. The effective method to reduce erosion and wear of gun bore [J]. *Defense Manufacturing Technology*, 2018(01): 44-46.
- [26] 梁西瑶. 微细滑石粉缓蚀剂降烧蚀性能研究 [D]. 成都: 西南交通大学, 2000.
LIANG Xi-yao. Research on erosion reducing properties of the inhibitor with fine talcum powder [D]. Chengdu: Southwest Jiaotong University, 2000.
- [27] 李洪广, 闫军, 杜仕国, 等. 火炮身管缓蚀剂技术研究进展 [J]. 火炮发射与控制学报, 2012(04): 103-106.
LI Hong-guang, YAN Jun, DU Shi-guo, et al. Research advance of erosion inhibitor technology in gun barrel [J]. *Journal of Gun Launch & Control*, 2012(04): 103-106.
- [28] 郑双, 刘波, 刘少武, 等. 新型有机硅缓蚀剂在小口径武器装药中的应用 [J]. 含能材料, 2011, 19(3): 335-338.
ZHENG Shuang, LIU Bo, LIU Shao-wu, et al. Application of a new agent of low erosion in the small caliber weapon [J]. *Chinese Journal of Energetic Materials (Hanneng Cailiao)*, 2011, 19(3): 335-338.
- [29] 李强, 魏伦, 崔艳芳, 等. 含新型有机硅缓蚀剂的制备及性能研究 [J]. 火炸药学报, 2020, 43(2): 225-229.
LI Qiang, WEI Lun, CUI Yan-fang, et al. Study on preparation and properties of a new type of silicone ablation inhibitor [J]. *Chinese Journal of Explosives & Propellants*, 2020, 43(2): 225-229.
- [30] 林少森, 杜仕国, 鲁彦玲, 等. 一种发射药用缓蚀剂的制备及表征 [J]. 兵器装备工程学报, 2019, 40(4): 26-29.
LIN Shao-sen, DU Shi-guo, LU Yan-ling, et al. Preparation and characterization of a novel inhibitor for propellant [J]. *Journal of Ordnance Equipment Engineering*, 2019, 40(4): 26-29.
- [31] 林少森, 杜仕国, 鲁彦玲, 等. 脲醛树脂/TiO₂ 复合微球缓蚀剂的制备及性能表征 [J]. 含能材料, 2020, 28(6): 484-490.
LIN Shao-sen, DU Shi-guo, LU Yan-ling, et al. Preparation and characterization of urea-formaldehyde/TiO₂ composite mi-

- erosion inhibitor [J]. *Chinese Journal of Energetic Materials(Hanneng Cailiao)*, 2020, 28(6): 484-490.
- [32] 王彦, 刘勋, 李彬, 等. 新型高温润滑自修复缓蚀剂的设计及其缓蚀性能[J]. 西南科技大学学报, 2023, 38(4): 39-44.
WANG Yan, LIU Xun, LI Bin, et al. Design and the corrosion inhibition performance of a new high-temperature lubrication and self-healing corrosion inhibitor [J]. *Journal of Southwest University of Science and Technology*, 2023, 38(4): 39-44.
- [33] 樊伟, 崔艳芳, 田甜, 等. 稀土氧化物作为缓蚀添加剂隔热机理研究[J]. 兵器材料科学与工程, 2018, 41(5): 62-65.
FAN Wei, CUI Yan-fang, TIAN Tian, et al. Thermal insulation mechanism of rare earth oxides as erosion reducing additive [J]. *Ordnance Material Science and Engineering*, 2018, 41(5): 62-65.

Preparation and Performance of a Silicon/Modified Nano TiO₂/Paraffin Based Composite Erosion Inhibitor

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Abstract: To reduce the erosion of R2 high-energy propellant, a new composite erosion inhibitor based on silicon/modified nano TiO₂/paraffin was designed and prepared. The erosion-reducing performance of the new type of composite erosion inhibitor was studied by a semi-closed bomb test with the standard erosion inhibitor as the reference material. The erosion inhibition mechanism of new composite erosion inhibitor was studied by scanning electron microscope-energy dispersive spectrum (SEM-EDS), and its effect on the static combustion property of propellant was investigated using a closed bomb. The results show that the new composite erosion inhibitor has a significant effect on reducing erosion. The erosion inhibition rate can reach 34.24% when the addition of erosion inhibitor is 5%. Decamethylcyclotrasiloxane (D5) in the erosion inhibitor is decomposed at high temperature, and the silicon oxide nanoparticles produced by the decomposition can effectively block the carburization reaction by adhering to the inner wall of the erosion tube. R2 propellant added with new composite erosion inhibitor has higher combustion progressivity, therefore the energy is released at the later stage of combustion which is beneficial to reduce the erosion. The new composite erosion inhibitor has great applied potential.

Key words: erosion inhibition; silicone erosion inhibitor; high-energy propellant; composite material

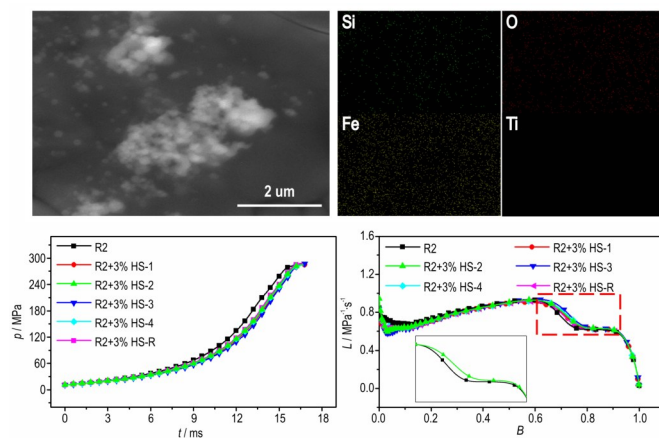
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图文摘要:



A new composite erosion inhibitor based on silicon/modified nano TiO_2 /paraffin was designed and prepared to reduce the erosion of R2 high-energy propellant. Its erosion-reducing performance was studied using a semi-closed bomb test with the standard erosion inhibitor as the reference material. The erosion inhibition mechanism of new composite erosion inhibitor was investigated using scanning electron microscope-energy dispersive spectrum (SEM-EDS), and its effect on the static combustion property of propellant was examined using a closed bomb.