文章编号:1006-9941(2018)12-1061-13

微纳米含能材料研究进展

李凤生,刘 杰
(南京理工大学化工学院国家特种超细粉体工程技术研究中心,江苏 南京 210094)

摘 要: 微纳米含能材料由于其小尺寸效应、密实效应、高表面能与高表面活性,表现出优异的性能并获得良好的应用效果。基于国内外学者的相关研究工作,综述了当前微纳米含能材料制备所采用的重结晶技术、粉碎技术,以及微纳米含能材料的干燥技术、粒度与形貌表征方法、感度随粒度大小变化机理、应用方向及效果等方面的研究进展。指出微纳米含能材料今后应重点加强基础理论、模拟仿真、应用作用机制及工程化放大与实际应用等方面的研究工作,使微纳米含能材料尽快转入工程化应用,以加快高能固体推进剂、混合炸药、发射药以及火工烟火药剂的发展并提升其性能。

关键词: 微纳米;含能材料;制备;表征;机理;应用
中图分类号: TJ55; O64 **文献标志码:** A **DOI:** 10.11943/CJEM2018280

1 引 言

“纳米”概念在20世纪中期被提出,但纳米材料的应用却在4-5世纪就已经开始了,如教堂彩色玻璃、银版照相术等。通常,纳米材料的三维尺寸中至少一维尺寸小于100 nm,包含颗粒(粉体)、薄膜、纤维等[1-2]。对于纳米粉体材料,其往往不是单一尺度的颗粒群,而是同时含有不同尺度的纳米颗粒,或者还含有亚微米级甚至微米级(通常指10 μm以下)颗粒;并且,从应用情况来看,虽然目前真正大规模实际应用的主要是亚微米或微米粉体材料,但这其中也往往含有纳米级颗粒。所以,纳米、亚微米及微米材料很难严格区分。因而,许多研究机构将微米、亚微米及纳米材料归于一类开展研究,如清华大学就成立了微纳米研究中心、微纳米学会。对于含能材料的研究,亦是如此。

对于微纳米单质含能材料,学者们早期寄望小尺寸颗粒内部产生的高压应力能伴随有额外的能量释放,后来的理论及实验证明,在实际应用的尺度范围内(如:30~100 nm)并没有表现出明显的能量优势。但单质含能材料的颗粒尺寸大小及分布对其感度与热分解特性产生显著的影响,并且对固体推进剂、混合炸药等的力学性能、燃烧/爆炸性能、感度等也会产生显著的影响,因而这也促使研究者全力开展微纳米单质含能材料(如黑索今(RDX)、奥克托今(HMX)、六硝基六氮杂异伍兹烷(CL-20)、三氨基三硝基苯(TATB)、六硝基芪(HNS)、1,1-二氨基-2,2-二硝基乙烯(FOX-7)、1-氧-2,6-二氨基-3,5-二硝基吡嗪(LLM-105)等)的制备技术与装备研究。在微纳米复合含能材料、尤其是纳米复合含能材料方面,学者们也开展了大量的研究工作[3]。由于这种复合体系具有小的临界直径,高反应速率以及大放热量,适用于作为“爆炸芯片”,并且有些性能优异的纳米含能材料具有非常快的燃烧速度,可以应用于多种领域。例如,负载有高氯酸钠的纳米多孔硅膜的燃烧速度超过3000 $m\cdot s^{-1}$[4]。但这种复合体系中诸多反应的引发与传播机制,至今仍没有完全彻底揭示。

微纳米含能材料的颗粒尺寸大小、形状与形貌、粒度分布、晶型结构、表面状态、分散性与流散性等,对其应用效果影响很大。这些特性与微纳米含能材料的制备技术、干燥技术、表面处理技术及应用技术直接相

收稿日期: 2018-09-30; **修回日期:** 2018-10-15
网络出版日期: 2018-10-30
基金项目: 国家自然科学基金资助(51606102)
作者简介: 李凤生(1946-),男,教授、博士生导师,主要从事含能材料高品质微纳米化制备与高效分散应用方面的理论、技术、装备及工程化与产业化推广应用研究。e-mail:lfs_njust@126.com
刘杰(1987-),男,副教授、硕士生导师,主要从事微纳米含能材料制备与应用研究。e-mail:jie_liu1987@163.com

引用本文: 李凤生,刘杰. 微纳米含能材料研究进展[J]. 含能材料,2018,26(12):1061-1073.
LI Feng-sheng,LIU Jie. Advances in Micro-nano Energetic Materials[J]. *Chinese Journal of Energetic Materials(Hanneng Cailiao)*,2018,26(12):1061-1073.

关。本文将重点针对微纳米单质含能材料，结合制备、干燥、表征、机理及应用等方面的研究进展进行综述。

2 微纳米含能材料制备与干燥技术

2.1 微纳米含能材料制备技术

采用重结晶技术制备微纳米含能材料时，首先将含能材料颗粒变为分子状态，如将含能材料溶解到某种溶剂或复合溶剂中形成溶液分子，然后通过控制溶液体系过饱和度，采用将分子状态的含能材料引入非溶剂、冷却降温、蒸发浓缩等手段，使含能材料分子重结晶析出，通过控制重结晶工艺参数，如冷却速度、溶液浓度、搅拌速度、温度、溶液稀释速度、表面活性剂用量等，获得微纳米含能材料颗粒。

如采用溶剂-非溶剂重结晶法，通过优选溶剂和非溶剂，控制溶液浓度、滴加速度、搅拌强度等参数，制备得到了微纳米RDX颗粒[5-8]，微纳米HMX颗粒[9-12]，纳米CL-20[13-14]，微纳米TATB颗粒[15-16]，以及微纳米HNS颗粒[17-20]及微纳米HNS混合炸药颗粒[21-22]。另外，还采用该方法制备得到了纳米RDX/聚合物复合含能材料[23]。采用喷雾干燥重结晶法，通过将含能材料溶解在特定溶剂中，使含能材料溶液雾化成小液滴，并在一定加热温度下迅速脱除溶剂，分别制备得到了微纳米RDX[24-29]，亚微米级HMX[30]，亚微米级TATB[31]，以及纳米RDX/粘结剂复合粒子[32-34]和超细CL-20/粘结剂复合粒子[35]。采用超临界流体重结晶法，以CO_2为溶剂，通过使溶有RDX的超临界CO_2溶液迅速膨胀（如图1所示），制备得到亚微米或纳米级RDX颗粒[36-39]，或者以CO_2为非溶剂，通过控制溶液的过饱和度，制备得到微纳米RDX或HMX[40-46]和亚微米级CL-20颗粒[47-48]。还通过超临界流体技术，制备得到了纳米RDX/聚合物复合含能材料[49]。采用喷射重结晶法，通过控制溶剂和抗溶剂种类、表面活性剂种类及用量，制备得到了微纳米RDX、HMX颗粒[50-53]，亚微米级CL-20颗粒[54-56]，微纳米TATB颗粒[57-58]，以及超细LLM-105颗粒[59]。采用溶胶-凝胶重结晶法，通过控制溶液浓度、前驱体种类、粘结剂种类等参数，制备得到了纳米RDX颗粒[60]、RDX基纳米复合含能材料[61]和HMX基纳米复合含能材料[62]以及CL-20基纳米复合含能材料[63]。采用静电喷雾重结晶法，通过控制含能材料溶液浓度、静电电压等，制备得到了微纳米RDX颗粒及RDX/NQ（硝基胍）复合含能材料[64-65]，微纳米CL-20颗粒及CL-20/NC（硝化纤维素）复合含能材料[66]。此外还采用超声辅助喷雾法和气动喷雾法制备得到了超细HMX颗粒[67]和超细CL-20颗粒[68]。

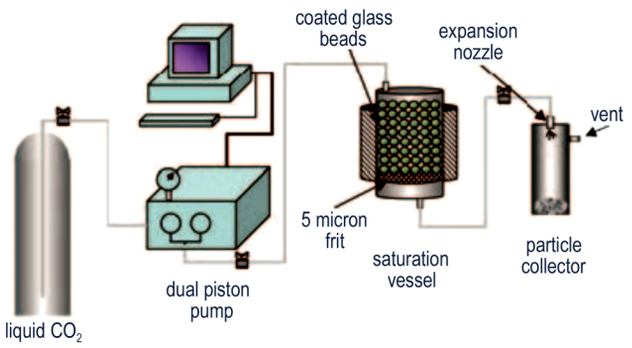


图1 超临界流体快速膨胀法制备微纳米含能材料原理示意图[37]

Fig. 1 The schematic principle diagram of preparing micro-nano energetic materials by Rapid Expansion of Supercritical Solutions (RESS) method[37]

采用粉碎技术制备微纳米含能材料，是通过控制球磨粉碎力场、运动部件高速旋转所产生的撞击与剪切粉碎力场（流能粉碎）、超声粉碎力场、高速旋转剪切式粉碎力场（胶体磨）等，以及物料浓度、分散剂种类、表面活性剂种类及用量等参数，制备微纳米含能材料。

如采用机械球磨法，通过在粉碎过程中加入异丁醇等高沸点表面活性剂，以0.02 kg/批制备得到了纳米级RDX[69]；以水为分散介质，通过使用单腔防爆型可远程控制设备，以0.5~0.6 kg/批制备得到了微米级超细HMX[70]；通过在粉碎过程中加入高沸点表面活性剂HFE，以0.1~0.4 kg/批制备得到了亚微米级CL-20[71]，或以水和乙醇为研磨介质，将混合浆料输入到研磨腔中进行单腔循环粉碎研磨，以0.3~0.5 kg/批制备超细CL-20[72]；使用一次可放入4个球磨罐的PM400型高能行星球磨机，单次产量为0.08 kg，以蒸馏水和乙醇为分散介质，制备纳米级TATB[73]和纳米级HNS[74]。同时还采用机械球磨粉碎法制备纳米尺度共晶炸药[75-76]，如HMX/CL-20共晶，以及RDX、HMX或CL-20基复合含能材料[77]。采用流能粉碎法，通过控制物料浓度、转子转速、粉碎时间等参数，制备超细RDX、HMX颗粒[78]、平均粒度约5 μm的超细CL-20样品[79]，以及超细HNS[80]颗粒。采用超声粉碎法，通过控制超声波功率、物料浓度、粉碎时间等，对粗颗粒含能材料进行初步粉碎细化[81-82]，制备得到了超细TATB颗粒[83]。

张小宁[84-87]、何得昌等[88-94]还采用高速撞击流粉碎法，通过控制撞击压力、粉碎次数、物料浓度、分散剂种类及用量等工艺参数，制备得到了微纳米RDX、

HMX颗粒，并在超声波辅助作用下，制备得到了亚微米级TATB颗粒；魏田玉[95]、曾贵玉[96,99-101]、刘俊志[97]等采用气流粉碎法，通过控制气流压力、粉碎次数、表面活性剂种类及用量等参数，制备得到了超细RDX、HMX，以及亚微米级TATB颗粒。还有学者采用胶体磨粉碎机，制备得到了平均粒度大于20 μm的RDX、HMX样品[102]。

为了解决安全、高效、高品质、大批量制备微纳米含能材料的难题，本课题组提出了“微力高效精确施加”粉碎原理（如图2所示）[103]，研制出了HLG型微纳米粉碎机，以水和少量低沸点试剂配制成分散液，使用多工位微纳米化粉碎机，实现连续化生产和远程自动化控制，制备微米、亚微米及纳米级含能材料RDX、HMX（如图3所示）、CL-20、TATB、HNS等，产品粒度30 nm~10 μm可调、可控，单批产量达100 kg以上[104-111]，已在工厂实施应用，建成了微纳米化粉碎生产线；基于该技术还可制备HMX/TATB、CL-20/TATB复合粒子[112]。

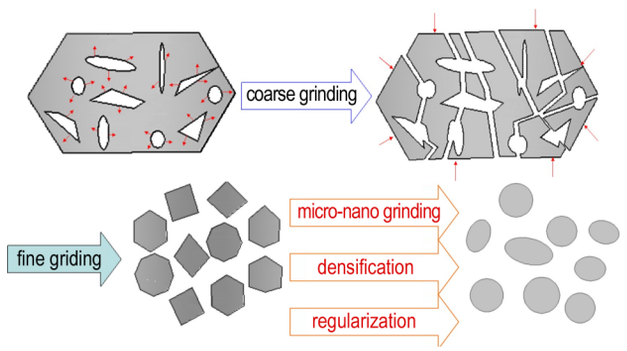


图2 “微力高效精确粉碎”原理制备微纳米含能材料示意图[103]

Fig.2 The schematic diagram of preparing micro-nano energetic materials by the principle of tiny grinding force being exactly given to materials[103]

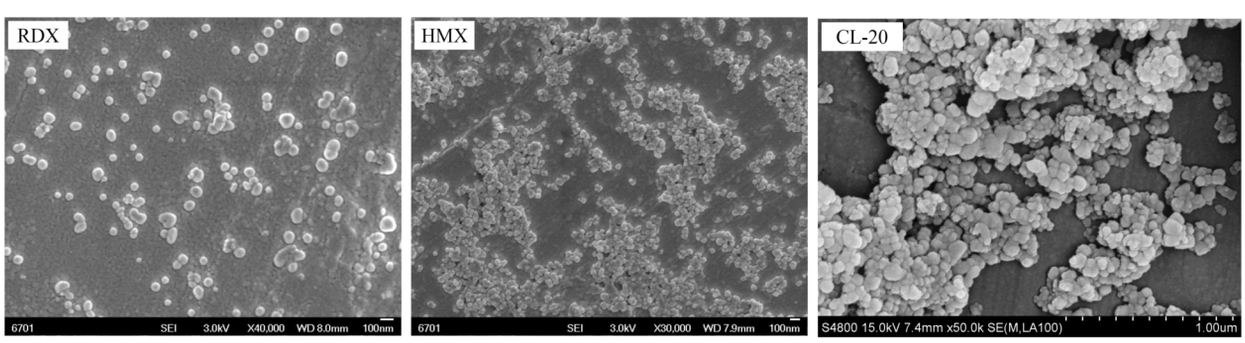


图3 基于“微力高效精确粉碎”原理制备的纳米RDX、HMX和CL-20电镜照片[103]

Fig.3 The SEM images of RDX, HMX and CL-20 prepared based on the principle of tiny grinding force being exactly given to materials[103]

采用重结晶技术制备微纳米含能材料时，如超临界流体重结晶技术、喷射重结晶技术、溶胶-凝胶重结晶技术等，往往工艺比较复杂，重复稳定性较难控制，并且存在溶剂所引起的环保和成本问题，因而目前尚未见实现大规模稳定制备方面的研究报导。采用粉碎技术制备微纳米含能材料时，工艺重复稳定性好、无溶剂引起的环保问题、成本较低，一旦在粉碎装备方面取得突破，便易于实现工程化放大。当前，基于“微力高效精确施加”原理的粉碎技术及装备均已突破，已经能够实现微纳米含能材料安全、高品质、大批量粉碎制备。

2.2 微纳米含能材料干燥技术

对于采用湿法制备得到的微纳米含能材料颗粒，需进行干燥处理。学者们通常采用普通水浴（油浴）烘箱[73]或真空烘箱[28,69,113]对微纳米含能材料进行干燥，首先对浆料样品进行抽滤，然后再烘干，或者先加入表面活性剂（如聚乙烯吡咯烷酮（PVP））与样品充分混匀后，再抽滤、烘干，以此减少微纳米含能材料颗粒团聚。

也有学者采用机电一体式冷冻干燥设备对微纳米含能材料样品进行干燥。如在干燥前加入表面活性剂PVP，并将样品抽滤为滤饼，再通过冷冻干燥得到纳米级TATB[73]，或者先将样品抽滤、分离，再进行冷冻干燥制得超细HNS[19,80]、亚微米级TATB[100]；或者先对样品进行液氮快速冷冻，再采用冷冻干燥得到超细FOX-7（如图4所示）[114]。还有学者采用机电一体式冷冻干燥设备对复合含能材料进行干燥。如先将RDX基纳米复合含能材料体系中的溶剂丁内酯置换为乙醇，再将乙醇用水置换，然后才进行冷冻干燥，干燥结束后再对样品进行干法粉碎[115]；或者先对CL-20基纳米复合含能材料进行冷冻干燥，再对干燥后的样品进行干法粉碎，得到微纳米复合含能材料粉末[63,116]；亦或者首先对样品采用液氮快速冷冻，然后

再进行冷冻干燥，最终获得CL-20基纳米复合含能材料[117]。

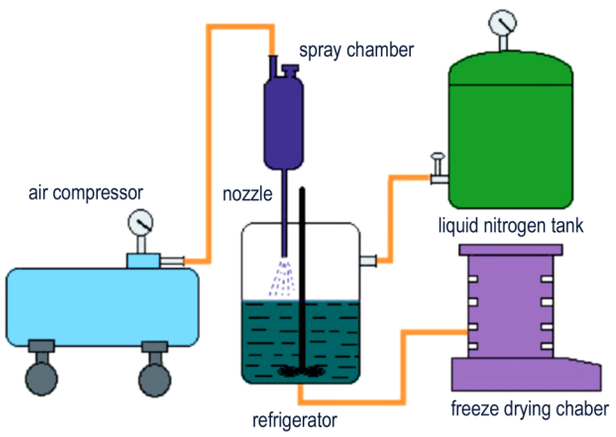


图4 采用液氮辅助预冻冷冻干燥法原理示意图[114]

Fig. 4 The schematic principle diagram of liquid nitrogen assisted freeze drying method abroad[114]

针对微纳米含能材料安全、高效、高品质干燥难题，本课题组提出了“膨胀撑离”防团聚干燥原理，研制出了LDD型机电分离式防爆结构的真空冷冻干燥设备，实现远程自动化控制，且干燥全过程不需添加任何物质，获得不团聚、分散性良好的微米、亚微米及纳米含能材料干粉，干燥后产品颗粒不长大，单批产量达100 kg以上[105-110]，已在工厂实施应用，建成了干燥生产线。

3 形貌与粒度表征方法

含能材料的形貌、平均粒度与粒度分布对其感度、装填密度及应用效果有显著的影响。学者们通常采用显微镜成像技术对含能材料颗粒形貌进行定性的分析。与同粒度非球形颗粒相比，球形含能材料颗粒比表面积比小、表面能低、流散性好，表现出感度低、工艺性能好、装填密度高等优势，因而含能材料颗粒球形度的定量表征也至关重要。形状因子是对颗粒形状进行定量表征的参数，有9种定义方法[118]。通常采用基于二维图像分析的形状因子——圆度（式（1））来定量表征含能材料颗粒的球形度[119-120]。

$$\Phi = \frac{4\pi A}{P^2} \tag{1}$$

式中，Φ为颗粒圆度，无量纲；A为颗粒投影面积，m^2；P为颗粒投影周长，m。

首先采用光学显微镜或电子显微镜观察并记录含能材料样品颗粒形貌图像，然后结合图像处理软件（如MATLAB）对显微图像中颗粒投影面积和周长进行计算，代入公式（1）即可求得含能材料样品颗粒（或颗粒群）的圆度，进而定量表征球形度。

对于含能材料颗粒或颗粒群的粒度表征，学者们通常采用粒度分布检测技术或者显微镜成像技术进行研究。如采用光学显微镜（OM）、扫描电子显微镜（SEM）、透射电子显微镜（TEM）、原子力显微镜（AFM）等，对含能材料颗粒大小进行表征，并结合图像处理软件（如Nano Measurer）对显微镜照片中颗粒大小进行标注，然后经过软件统计计算得到样品的粒度分布。这种方法对颗粒大小均匀的样品比较适用，尤其是对尺寸只有几纳米的量子点进行表征时，具有较好的效果。然而，采用这种方法对微纳米含能材料颗粒群的粒度分布进行表征时，由于其取样量很少、取样时受人为因素影响很大，难以有效表征样品真实的粒度分布。

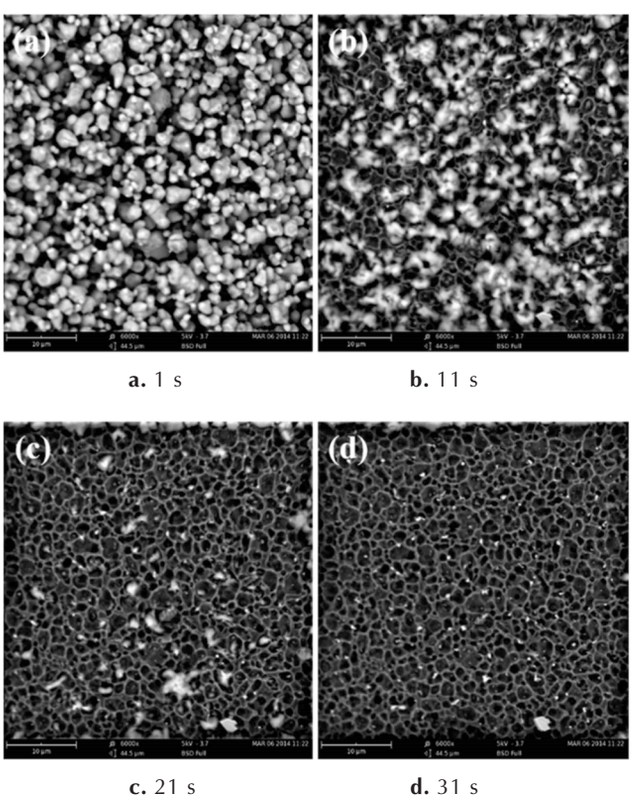
粒度分布测试仪由于其取样量大进而能够很好地代表样品真实状态，并且测试过程自动进行、受人为因素干扰小，广泛应用于含能材料颗粒群粒度分布的表征。首先将含能材料样品用非溶剂（分散剂）初步分散，然后加入表面活性剂（如吐温、司班、十二烷基磺酸钠）对样品进一步防团聚分散，之后在超声作用下将颗粒充分分散在分散剂中，形成均匀、稳定的悬浮液，最后将悬浮液加入粒度测试仪进样器中，由粒度测试仪自动进行粒度分析检测，获得含能材料样品粒度分布曲线。这种方法方便、快捷、表征结果能够很好的反应样品颗粒群的粒度分布情况。当前，对于10 μm以上含能材料颗粒群的粒度分布表征，测试结果误差相对较小。然而对于粒度10 μm以下的样品，由于颗粒极容易团聚，导致各个单位采用粒度分析仪对同一样品的测试结果偏差较大，这主要是由于样品分散状态不同所导致。当样品分散工艺参数不同时，如样品浓度、表面活性剂种类与用量及状态、超声分散方式及分散时间、样品温度等，将引起颗粒分散状态的改变，进而对测试结果产生显著的影响，急需对测试标准进行统一，以适应微纳米含能材料发展需求。

4 含能材料感度随粒度大小变化机理

英国学者Bowden等[121]于1952年提出热点理论，后续研究者普遍基于该理论研究含能材料受到外界刺激作用时的起爆过程，尤其是含能材料颗粒群在外界刺激作用下形成热点后，热点之间的相互作用以及热点成长为爆轰和爆轰传递等过程[122-123]，进而分

析不同状态下(如不同颗粒大小)颗粒群的起爆规律。学者们也大量采用差示扫描量热法(DSC)和动态真空安定性法(DVST)来计算热分解过程的速率常数与表观活化能[124-135],试图通过热效应来反推含能材料颗粒群在不同状态下的热分解过程,进而分析感度随粒度大小的变化机理。然而,这些研究工作都是假设外界刺激能量大于、甚至远大于颗粒群的临界激发能量,从测试结果反推感度变化原因,未直接对颗粒群自身临界激发能量开展研究,进而直观阐述含能材料颗粒群感度随粒度大小变化的机理。

本课题组立足含能材料颗粒群热分解临界激发能量,借助颗粒在受到电子能激发后会发生热分解变形(如图5所示)[136],且所需临界电子激发能随尺寸变化发生变化这一实验现象,提出基于临界电子激发能研究含能材料感度随粒度大小变化机理。通过研究热分解临界电子激发能的差异,以及颗粒临界电子激发能随粒度大小的变化规律,掌握含能材料颗粒群的平均临界电子激发能,揭示热分解历程变化的机理,进而阐述感度变化机理[137]。该研究工作可为含能材料性能优化和高效应用提供理论支持,并且可为其它活性物质(如强氧化剂)的热分解临界激发能量和性能变化机理研究提供理论方法与技术支持。



a. 1 s **b.** 11 s

c. 21 s **d.** 31 s

图5 高氯酸铵(AP)颗粒在电子束作用下发生分解变性的SEM照片[137]

Fig. 5 SEM photographs of the decomposition and denaturation of ammonium perchlorate (AP) particles occurring under electron beam irradiation for various time[137]

5 微纳米含能材料的应用方向及效果

微纳米含能材料在体系中作为固体粒子能起到增韧增强的效果[138-139],当一定含量微纳米含能材料颗粒应用于混合炸药、固体推进剂及发射药中后,可与聚合物(粘结剂)界面良好结合,形成均匀的物理交联点,颗粒越小,交联点越多、越致密,进而形成高交联密度的网络结构,使力学性能显著提高,尤其是固体推进剂的延伸率,可获得大幅度提升;同时还可降低感度、改善燃烧/爆炸性能。然而,微纳米含能材料含量也并非越高越好,当含量大于一定值后,其很难在体系中均匀分散,导致形成大量的团聚体使物理交联强度大大降低,进而引起力学性能急剧下降,甚至导致感度升高、燃烧/爆炸性能恶化。因此,可通过粒度级配,优化微纳米含能材料的配比组成,以实现战略与战术武器性能显著提升。

另外,含能材料(如HNS、TATB)亚微米及纳米化后,长脉冲冲击波感度降低、短脉冲冲击波感度提高,这可应用于新型冲击片起爆器件中,既能提高使用安全性,又能提高起爆灵敏度和稳定性。微纳米含能材料还可应用于高精度多点起爆网络中,实现起爆精度、安全性和灵敏度同时提高。通过结构设计和优化,进而显著促进战略与战术武器的发展。并且,微纳米化处理后可能引起含能材料反应历程的改变,进而可应用于诸多新的领域。

如在混合炸药方面,学者们以微纳米含能材料(如RDX、HMX、CL-20、TATB、LLM-105等)为主体炸药,替代混合炸药配方中的粗颗粒含能材料,制备得到了混合炸药样品并对其力学性能、感度、热分解特性、能量输出特性等进行了研究,结果表明当微纳米含能材料应用后,力学性能提高、撞击感度与长脉冲冲击波感度降低[140-153],能量输出提高[153],热分解反应活性增强[154],同时还表现出对短脉冲冲击波更加敏感的特性[155]。通过将超细HMX应用于传爆药中,可使传爆药的摩擦感度、撞击感度、长脉冲冲击波感度降低[156],能量输出增大[157]。将超细含能材料应用于起爆药中,可降低起爆能量、提高起爆可靠性[158-159]。

当微纳米RDX用于改性双基推进剂中后,可提高

推进剂的抗拉强度和杨氏模量[160]，并且还可降低摩擦感度和撞击感度，改善燃烧性能[103,161]。超细含能材料也可应用于复合推进剂中制备燃气发生器药剂[162]，当其用于火箭发动机装药时，在保证推进剂信号特征、能量、工艺与力学性能的同时，降低了高压压强指数[163]，最新研究还表明，超细含能材料还可显著降低复合推进剂的感度、大幅度提高延伸率。微纳米含能材料还可用于微点火芯片中[164-165]，以提高点火稳定性和成功率；如超细HNS由于短脉冲冲击波起爆能量低，还可用于冲击片雷管中，以提高起爆灵敏度、稳定性和可靠性[74,80,166]。

上述研究结果表明：当微纳米含能材料应用后，可显著改善混合炸药、固体推进剂等产品的性能，然而，不同学者的研究结果也有出现较大差异的情况。其中一个重要原因是微纳米含能材料的制备工艺不一样：如有重结晶工艺、也有粉碎工艺，还有的工艺在制备过程中加入了难以脱除的表面活性剂，引起产品颗粒表面状态、形貌、粒度分布、纯度等不一致，进而导致应用效果存在差异。另一重要原因是微纳米含能材料浆料的干燥方法不一样：存在水浴烘箱干燥、真空干燥、真空冷冻干燥等不同方式，导致所获得的干燥产品的分散状态和实际颗粒粒度产生显著的差异；如同一种含能材料浆料，采用普通水浴干燥后获得产品团聚结块、颗粒急剧长大，采用真空干燥后产品团聚和颗粒长大更明显，而采用真空冷冻干燥所获得的产品分散性良好、颗粒基本不长大，能很好的保持微纳米含能材料的优异特性[105-106]。因此，为了提高微纳米含能材料的应用效果，须在制备过程中尽量避免使用高沸点表面活性剂，还须采用真空冷冻干燥等防团聚/干燥方式防止产品团聚结块、颗粒长大。

6 结 论

（1）基于“微力高效精确施加”粉碎原理和“膨胀撑离”防团聚干燥原理，已经能够实现微纳米含能材料高品质粉碎与高效防团聚干燥制备，为适应国家智能化制造需求，仍需开展干燥过程实现连续化制造的理论与技术及装备研究，并进一步深入开展微纳米含能材料制备与干燥过程机理研究和模拟仿真研究，为高品质微纳米含能材料产品数字化与智能化制造提供理论和技术支撑。

（2）微纳米含能材料的高效应用应结合单质含能材料的粒度进行合理级配及复合含能材料的组成与结构调控两方面加以考虑，充分发挥小尺寸效应和表面效应以及微纳米结构的优势，以获得理想应用效果。

（3）微纳米含能材料的热分解反应历程及机制尚需深入研究，进而揭示其在固体推进剂、混合炸药、发射药及火工烟火药剂中的作用机理，为其结构优化与调控及高效应用提供理论支撑。

参考文献：

[1] 李凤生.超细粉体技术[M].北京：国防工业出版社，2000.
LI Feng-sheng. Technology of superfine powder[M]. Beijing: National Defence Industry Press, 2000.

[2] ISO, ISO/TS 27687. Nanotechnologies: terminology and definitions for nano-objects: nanoparticle, nanofibre and nanoplate. Geneva, Switzerland, ISO, 2008.

[3] Zachariah M R. Nanoenergetics: hype, reality and future[J]. *Propellants, Explosives, Pyrotechnics*, 2013, 38(1): 7.

[4] Becker C R, Apperson S, Morris C J, et al.Galvanic porous silicon composites for high-velocity nanoenergetics [J]. *Nano Letters*, 2011, 11: 803-807.

[5] 张永旭，吕春绪，刘大斌.重结晶法制备纳米RDX[J].火炸药学报，2005，28(1)：49-51.
ZHANG Yong-xu, Ln Chun-xu, LIU Da-bin. Preparation of RDX microcrystals with nanometer size by recrystalization[J]. *Chinese Journal of Explosives and Propellants*, 2005, 28(1): 49-51.

[6] 芮久后，王泽山，刘玉海，等.超细黑索今制备新方法[J].南京理工大学学报，1996，20(5)：385-388.
RUI Jiu-hou, WANG Ze-shan, LIU Yu-hai, et al. A New method for preparation of ultraf ine RDX crystals[J]. *Journal of Nanjing University of Science and Technology*, 996, 20 (5): 385-388.

[7] 李生慧，杨超，王天佑.液相法制备超细黑索今[J].火炸药学报，1994 (4)：23-25.
LI Sheng-hui, YANG Chao, WANG Tian-you. Preparation of ultrafine RDX by liquid phase method [J]. *Chinese Journal of Explosives and Propellants*, 1994 (4):23-25.

[8] Kumar R, Siril P F, Soni P. Preparation of nano-RDX by evaporation assisted solvent antisolvent interaction[J]. *Propellants, Explosives , Pyrotechnics*, 2014, 39(3): 383-389.

[9] ZHANG Yong-xu, LIU Da-bin, LÜ Chun-xu. Preparation and characterization of reticular nano-HMX[J]. *Propellants, Explosives, Pyrotechnics*, 2005, 30(6): 438-441.

[10] 马东旭，梁逸群，张景林.重结晶制备奥克托今(HMX)粒径及晶形的研究[J].陕西科技大学学报，2009，27(1)：54-57.
MA Dong-xu, LIANG Yi-qun, ZHANG Jing-lin. Study on the particle size and crystal form of HMX prepared by re-crystallization[J]. *Journal of Shaanxi University of Science and Technology*, 2009, 27(1): 54-57.

[11] Lee G D, Chae J S, Han S G, et al. Method for manufacturing β-HMX particles: KR2017057738[P], 2017

[12] Vinnikov V P, Generalov M B, Glinskii V P, et al. Method and apparatus for production of nanodispersed octogen or hexogen powder: RU2343138[P], 2009

[13] Bayat Y, Zeynali V. Preparation and characterization of nano-CL-20 Explosive[J]. *Journal of Energetic Materials*, 2011, 29(4): 281-291.

[14] Bayat Y, Zarandi M, Zarei M A, et al. A novel approach for preparation of CL-20 nanoparticles by microemulsion method [J]. *Journal of Molecular Liquids*, 2014, 193(5): 83-86.

[15] 曾贵玉, 聂福德, 赵林, 等. 一种微纳米TATB炸药颗粒的制备方法: CN 102924192 [P], 2013.
ZENG Gui-yu, NIEFu-de, ZHAO Lin, et al. A preparation method of micro-nano TATB explosive particles: CN102924192A[P], 2013.

[16] 王保国, 张景林, 陈亚芳. 亚微米级TATB的制备工艺条件对其粒径的影响[J]. 火炸药学报, 2008, 31(1): 30-33.
WANG Bao-guo, ZHANG Jing-lin, CHEN Ya-fang. Effect of preparation technological condition on particle size of sub-micron TATB[J]. *Chinese Journal of Explosives and Propellants*, 2008, 31(1): 30-33.

[17] 王晶禹, 黄浩, 王培勇, 等. 高纯纳米HNS的制备与表征[J]. 含能材料, 2008, 16(3): 258-261.
WANG Jing-yu, HUANG Hao, WANG Pei-yong, et al. Preparation and characterization of high purity nano HNS[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2008, 16(3): 258-261.

[18] 尚雁, 叶志虎, 王友兵, 等. HNS-Ⅳ的制备及粒径、形貌控制[J]. 含能材料, 2011, 19(3): 299-304.
SHANG Yan, YE Zhi-hu, WANG You-bing, et al. Preparation, particle size and crystal control of HNS-IV[J]. *Chinese Journal of Energetic Materials* (*Hanneng Cailiao*), 2011, 19(3): 299-304.

[19] Quinlin W T, Thorpe R, Sproul M L, Cates D M. Continuous aspiration process for manufacture of ultra-fine particle hexanitrostilbene: US6844473[P], 2005.

[20] Lashkov V N, Egorycheva E N. Precipitation method for obtaining ultrafine hexanitrostilbene explosive: RU2337902 [P], 2008

[21] 晏蜜, 刘玉存, 宋思维, 等. 超细HNS/ANPZO混晶炸药的制备和性能研究[J]. 科学技术与工程, 2017, 17(4): 208-212.
YAN Mi, LIU Yu-cun, SONG Si-wei, et al. Preparation and characterization of superfine HNS/ANPZO mischcrystal explosive[J]. *Science and Technology and Engineering*, 2017, 17(4): 208-212.

[22] 王平, 刘永刚, 张娟, 等. 超细HNS/HMX混晶的制备与性能[J]. 含能材料, 2009, 17(2): 187-189.
WANG Ping, LIU Yong-gang, ZHANG Juan, et al. Preparation and performance of HNS/HMX superfine mischcrystal[J]. *Chinese Journal of Energetic Materials* (*Hanneng Cailiao*), 2009, 17(2): 187-189.

[23] Qiu H, Stepanov V, Di S A, et al. RDX-based nanocomposite microparticles for significantly reduced shock sensitivity [J]. *Journal of Hazardous Materials*, 2011, 185(1): 489-493.

[24] 陈厚和, 孟庆刚, 曹虎, 等. 纳米RDX粉体的制备与撞击感度[J]. 爆炸与冲击, 2004, 24(4): 382-384.
CHEN Hou-he, MENG Qing-gang, CAO Hu, et al. Preparation and impact sensitivity of nanometer explosive powder of RDX [J]. *Explosion and Shock Waves*, 2004, 24(4): 382-384.

[25] 马慧华. 纳米RDX的制备与性能研究[D]. 南京: 南京理工大学, 2004.
MA Hui-hua. Preparation and properties of nano RDX[D]. Nanjing: Nanjing University of Science and Technology, 2004

[26] 陈厚和, 马慧华, 裴艳敏, 等. 纳米黑索今的制备及其机械感度[J]. 弹道学报, 2003, 15(3): 11-13,18.
CHEN Hou-he, MA Hui-hua, PEI Yan-min, et al. The preparing technology and mechanical sensitivity of nanometer RDX [J]. *Journal of ballistics*, 2003, 15(3): 11-13,18.

[27] Klaumünzer M, Pessina F, Spitzer D. Indicating inconsistency of desensitizing high explosives against impact through recrystallization at the nanoscale[J]. *Journal of Energetic Materials*, 2017, 35(4): 375-384.

[28] Kim J W, Shin M S, Kim J K, et al. Evaporation crystallization of RDX by ultrasonic spray [J]. *Industrial and Engineering Chemistry*, 2011, 50(21): 12186-12193.

[29] Radacsi N, Stankiewicz A I, Horst J H T. Cold plasma synthesis of high quality organic nanoparticles at atmospheric pressure [J]. *Journal of Nanoparticle Research*, 2013, 15(2): 1445.

[30] Risse B, Schnell F, Spitzer D. Synthesis and desensitization of nano-beta-HMX [J]. *Propellants, Explosives, Pyrotechnics*, 2014, 39(3): 397-401.

[31] Hotchkiss P J, Wixom R R, Tappan A S, et al. Nanoparticle triaminotrinitrobenzene fabricated by carbon dioxide assisted nebulization with a bubble dryer[J]. *Propellants, Explosives, Pyrotechnics*, 2014, 39(3): 402-406.

[32] Qiu H, Stepanov V, Di S A, et al. RDX-based nanocomposite microparticles for significantly reduced shock sensitivity [J]. *Journal of Hazardous Materials*, 2011, 185(1): 489-493.

[33] Stepanov V, Qiu, H, Di S A, et al. Preparation and properties of nanostructured RDX/polymr compositions[C]//International Annual Conference of ICT, 2010, stepa1/1-stepa1/6.

[34] Pessina F, Schnell F, Spitzer D. Tunable continuous production of RDX from microns to nanoscale using polymeric additives[J]. *Chemical Engineering Journal*, 2016, 291: 12-19.

[35] Stepanov V, Qiu, H, Surapaneni A. Production of novel CL-20-based compositions by spray drying [C]//International Annual Conference of ICT. 2011:110/1-110/6.

[36] Stepanov V, Anglade V, Balas Hummers W A, et al. Production and sensitivity evaluation of nanocrystalline RDX-based explosive compositions[J]. *Propellants, Explosives, Pyrotechnics*, 2011, 36(3): 240-246.

[37] Stepanov V, Krasnoperov L N, Elkina I B, et al. Production of nanocrystalline RDX by rapid expansion of supercritical solutions[J]. *Propellants, Explosives, Pyrotechnics*, 2005, 30(3): 178-183.

[38] Matsunaga T, Chernyshev A V, Chesnokov E N, et al. In situ optical monitoring of RDX nanoparticles formation during rapid expansion of supercritical CO_2 solutions[J]. *Physical Chemistry Chemical Physics*, 2007, 9(38): 5249-5259.

[39] Stepanov V, Anglade V, Balas W, et al. Processing and characterization of nanocrystalline RDX[J]. *Inventi Impact Pharm Analysis and Quality Assurance*, 2008(1): 54/1-54/15.

[40] 陈亚芳, 王保国, 张景林, 等. 超临界流体反溶剂法制备超细HMX传爆药[J]. 火炸药学报, 2011, 34(5): 46-49.
CHEN Ya-fang, WANG Bao-guo, ZHANG Jing-lin, et al. Preparation of ultra-fine boostere explosive based on HMX by supercritical anti-solvent technique[J]. *Chinese Journal of Explosives and Propellants*, 2011, 34(5): 46-49.

[41] 高振明, 蔡建国, 龙宝玉, 等. 超临界CO_2法制备超细HMX颗粒[J]. 火炸药学报, 2008, 31(4): 22-26.
GAO Zhen-ming, CAI Jian-guo, LONG Bao-yu, et al. Prepara-

tion of HMX ultrafine particles by supercritical CO_2 method [J]. *Chinese Journal of Explosives and Propellants*, 2008, 31(4): 22-26.

[42] 赵瑞先.超临界流体制取超微细高能炸药新工艺[J].国防技术基础, 2003(1): 26-28,39.
ZHAO Rui-xian. New technology for preparing ultra-fine high-energy explosives by supercritical fluid[J]. *National Defense Technical Foundation*, 2003 (1): 26-8,39.

[43] Lee B M, Kim D S, Lee Y H, et al. Preparation of submicron-sized RDX particles by rapid expansion of solution using compressed liquid dimethyl ether[J]. *Journal of Supercritical Fluids*, 2011, 57(3): 251-258.

[44] Matsuzaki S, Okitsu T, Ouchi K, et al. Crystal shape control of RDX using supercritical carbon dioxide[J]. *Science and Technology of Energetic Materials*, 2005, 66(6): 436-442.

[45] Dou H, Kim K H, Lee B C, et al. Preparation and characterization of cyclo-1,3,5-trimethylene-2,4,6-trinitramine(RDX) powder: comparison of microscopy, dynamic light scattering and field-flow fractionation for size characterization[J]. *Powder Technology*, 2013, 235: 814-822.

[46] Bayat Y, Pourmortazavi S M, Iravani H, et al. Statistical optimization of supercritical carbon dioxide antisolvent process for preparation of HMX nanoparticles[J]. *Journal of Supercritical Fluids*, 2012, 72: 248-254.

[47] 尚菲菲，张景林，张小连，等.超临界流体增强溶液扩散技术制备纳米CL-20及表征[J].火炸药学报, 2012, 35(6): 37-40.
SHANG Fei-fei, ZHANG Jing-lin, ZHANG Xiao-lian, et al. Preparation and characterization of nano-CL-20 with solution enhanced dispersion by supercritical fluids [J]. *Chinese Journal of Explosives and Propellants*, 2012, 35(6): 37-40.

[48] 陈亚芳，王保国，张景林，等.超临界GAS的工艺条件对CL-20粒度和晶型的影响 [J].火炸药学报, 2010, 33(3): 9-13.
CHEN Ya-fang, WANG Bao-guo, ZHANG Jing-lin, et al. Influence of supercritical gas anti-solvent technological conditions on particle size and modes of crystallization of CL-20[J]. *Chinese Journal of Explosives and Propellants*, 2010, 33(3): 9-13.

[49] He B, Stepanov V, Qiu H, et al. Production and characterization of composite nano-RDX by ress co-precipitation[J]. *Propellants, Explosives, Pyrotechnics*, 2015, 40(5): 659-664.

[50] 陈亚芳，王保国，张景林，等.高纯度亚微米级RDX的制备、表征与性能[J].火工品, 2010(2): 48-50.
CHEN Ya-fang, WANG Bao-guo, ZHANG Jing-lin, et al. Preparation, characterization and performances of high purity sub-micron RDX[J]. *Initiators and Pyrotechnics*, 2010(2): 48-50.

[51] 柴涛，张景林.主体炸药超细粒度级配对混合传爆药压药密度的影响研究[J].火炸药学报, 2002 (4): 71-72.
CHAI Tao, ZHANG Jing-lin. Effect of particle gradation of HMX on the compressibility of a typical booster explosive[J]. *Chinese Journal of Explosives and Propellants*, 2002 (4): 71-72.

[52] 王晶禹，张景林，徐文峥.微团化动态结晶法制备超细HMX炸药[J].爆炸与冲击, 2003, 23(3): 262-266.
WANG Jing-yu, ZHANG Jing-lin, XU Wen-zheng. Utrafine HMX explosive preparation with atomizing kinetic crystal method [J]. *Explosion and Shock Waves*, 2003, 23(3): 262-266.

[53] 周得才，吕春玲，李梅，等.粒度对硝胺类炸药烤燃热感度的影响[J].含能材料, 2011, 19(4): 442-444.
ZHOU De-cai, LV Chun-ling, Li Mei, et al. Effect of particle size of nitroamine explosives on cook-off sensitivity[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2011, 19(4): 442-444.

[54] 王瑞浩，晋日亚，张伟，等.超细ε-HNIW的制备及表征[J].火工品, 2015 (1): 34-37.
WANG Rui-hao, JIN Ri-ya, ZHANG Wei, et al. Preparation and characterization of ultrafineε-HNIW[J]. *Initiators and pyrotechnics*, 2015 (1): 34-37.

[55] 张亮，赖一顺.喷射法细化CL-20的实验与形貌表征[J].广东化工, 2018, 45(365): 58-59,69.
ZHANG Liang, LAI Yi-shun. Experiments and morphology characterization of ultrafine CL-20 by spray method [J]. Guangdong Chemical Industry, 2018, 45(365): 58-59,69.

[56] Wang J, Li J, An C, et al. Study on ultrasound- and spray-assisted precipitation of CL-20[J]. *Propellants , Explosives, Pyrotechnics*, 2012, 37(6): 670-675.

[57] 邵琴.TATB基PBX传爆药配方优化设计及性能研究[D].太原：中北大学, 2016.
SHAO Qin. Formulation optimization and performance test of TATB based PBX[D]. Taiyuan: North Central University, 2016.

[58] 邵琴，徐文铮，王晶禹，等.TATB基PBX配方研究及性能测试[J].火工品, 2015(5): 46-49.
SHAO Qin, XU Wen-zheng, WANG Jing-yu, et al. Formulation research and performance testof TATB-based PBX[J]. *Initiators and Pyrotechnics*, 2015(5): 46-49.

[59] 李玉斌，黄辉，李金山，等.一种含LLM-105的HMX基低感高能PBX炸药[J].火炸药学报, 2008, 32(5): 1-4.
LI Yu-bin, HUANG Hui, LI Jin-shan, et al. A new HMX-based low-sensitive high energy PBX explosive containing LLM-105 [J]. *Chinese Journal of Explosives and Propellants*, 2008, 32(5): 1-4.

[60] 宋小兰，李凤生，张景林，等.纳米RDX的制备及其机械感度和热分解特性[J].火炸药学报, 2008, 31(6): 1-4.
SONG Xiao-lan, LI Feng-sheng, ZHANG Jing-lin, et al. Preparation, mechanical sensitivity and thermal decomposition characteristics of RDX nanoparticles[J]. *Chinese Journal of Explosives and Propellants*, 2008, 31(6): 1-4.

[61] 晋苗苗，罗运军.硝化棉/黑索今纳米复合含能材料的制备与热性能研究[J].兵工学报, 2014, 35(6): 822-827.
JIN Miao-miao, LUO Yun-jun. Preparation and thermal properties of NC/RDX nano-composite energetic materials[J]. *Acta Armamentrii*, 2014, 35(6): 822-827.

[62] Nie F, Zhang J, Guo Q, et al. Sol-gel synthesis of nanocomposite crystalline HMX/AP coated by resorcinol-formaldehyde [J]. *Journal of Physics and Chemistry of Solids*, 2010, 71(2): 109-113.

[63] Tappan B C, Li Jun, Brill T B. Synthesis and characterization of energetic nanocomposites[C]//Proceedings of the NATAS Annual Conference on Thermal Analysis and Applications, 33rd, 2005: 095.36.986/1-8.

[64] 李博.硝基胍基复合含能材料的制备及表征[D].绵阳：西南科技大学, 2016.
LI Bo. Preparation and characterization of nitroguanidine composite energetic materials[D]. Mianyang: Southwest University of Science and Technology, 2016.

[65] Radacsi N, Stankiewicz A I, Creyghton Y L M, et al. Electrospray crystallization for high-quality submicron-sized crystals [J]. *Chemical Engineering and Technology*, 2011, 34(4): 624-630.

[66] 李梦尧.微纳米CL-20/NC的静电射流法制备[D].北京:北京理工大学, 2016.
LI Meng-yao.Fabrication of nano and micro particulates CL-20/NC by electrospinning and electrospray methods[D]. Beijing: Beijing Institute of Technology, 2016.

[67] 徐文峥, 庞兆迎, 王晶禹, 等.超声辅助喷雾法制备超细高品质HMX及其晶型控制[J].含能材料, 2018, 26(3): 260-266.
XU Wen-zheng, PANG Zhao-ying, WANG Jing-yu, et al. Ultrafine high quality HMX prepared by ultrasonic assisted spray method and its crystal type control[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2018, 26(3): 260-266.

[68] 徐文峥, 平超, 王晶禹, 等.两种喷雾结晶法制备超细CL-20[J].固体火箭技术, 2018, 41(2): 1-5.
XU Wen-zheng, PING Chao, WANG Jing-yu, et al. Ultrafine CL-20 prepared by two kinds of spraying crystallization method [J]. *Journal of Solid Rocket Technology*, 2018, 41(2): 1-5.

[69] Redner P, Kapoor D, Patel R, Chung M, Martin D. Production and characterization of nano-RDX[R]. 2006.

[70] Rossmann C, Heintz T, Herrmann M, et al. Production of ultrafine explosive particles in non-aqueous systems by bead milling technology[C]// International Annual Conference of ICT. 2013: 74/1-74/11.

[71] Aumelas A, Lescop P. Process of obtaining crystal charges of hexanitrohexaazaisowurtzitane (CL-20) of submicronic monomodal particle size distribution: FR3018807[P], 2015

[72] 焦清介, 张朴, 郭学永, 等.一种超细CL-20的制备装置及制备方法: CN103506194[P], 2014.
JIAO Qing-jie, ZHANG Pu, GUO Xue-yong, et al. A preparation device and preparation method of ultrafine CL-20: CN103506194[P], 2014.

[73] 宋小兰, 王毅, 刘丽霞, 等.机械球磨法制备纳米TATB及其表征[J].固体火箭技术, 2017, 40(4): 471-475.
SONG Xiao-lan, WANG Yi, LIU Li-xia, et al. Preparation and characterization of nanometer TATB by mechanical ball milling [J]. *Journal of Solid Rocket Technology*, 2017, 40(4): 471-475.

[74] 宋小兰, 王毅, 刘丽霞, 等.机械球磨法制备纳米HNS及其热分解性能[J].含能材料, 2016, 24(12): 1188-1192.
SONG Xiao-lan, WANG Yi, LIU Li-xia, et al.Thermal decomposition performance of nano HNS fabricated by mechanical ball milling[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2016, 24(12): 1188-1192.

[75] Patel R B, Qiu H, Stepanov V, et al. Single-step production method for nano-sized energetic cocrystals by bead milling and products: US9701592[P], 2017.

[76] Patel R B, Qiu H, Stepanov V, et al. Single-step production method for nano-sized energetic cocrystals by bead milling and products thereof: US9701592 B1[P], 2017.

[77] Patel R B, Stepanov V, Surapaneni A, et al. Bead milled spray dried nano-explosives: US9682895[P], 2017.

[78] 刘宏英, 邓国栋, 杨毅, 等.采用LS型超细粉碎机对几种单质炸药超细化研究[J].爆破器材, 2004, 33(5): 32-35.
LIU Hong-ying, DENG Guo-dong, YANG Yi, et al. Study on the superfine of explosive by LS superfine pulverizers[J]. *Explosive Materials*, 2004, 33(5): 32-35.

[79] Gerber P, Zilly B, Teipel U. Fine grinding of explosives[C]// International Annual Conference of ICT, 1998: 71.1-71.12.

[80] 雷波, 史春红, 马友林, 等.超细HNS的制备和性能研究[J].含能材料, 2008, 16(2): 138-141.
LEI Bo, SHI Chun-hong, MA You-lin, et al.Preparation and characterization of ultrafine HNS[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2008, 16(2): 138-141.

[81] Teipel U, Mikonsaari I.Size reduction of particulate materials [J]. *Chemie Ingenieur Technik*, 2002, 27(3): 168-174.

[82] Somoza C. Ultrasonic grinding of explosives: US5035363[P], 1991.

[83] 王平, 秦德新, 辛芳, 等.超声波在超细炸药制备中的应用[J].含能材料, 2003, 11(2): 107-109.
WANG Ping, QIN De-xin, XIN Fang, et al. Applications of ultrasonic technique in the preparation of ultrafine explosives[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2003, 11(2): 107-109.

[84] 张小宁, 徐更光, 王廷增.高速撞击流制备超细硝胺炸药的实验研究[J].含能材料, 1999, 7(3): 97-99.
ZHANG Xiao-ning, XU Geng-guang, WANG Ting-zeng. A study on preparation of ultra-fine nitroamine explosives by using high-speed impinging stream[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 1999, 7(3): 97-99.

[85] 张小宁, 徐更光, 王廷增.高速撞击流粉碎制备超细HMX和RDX的研究[J].北京理工大学学报, 1999, 19(5): 120-124.
ZHANG Xiao-ning, XU Geng-guang, WANG Ting-zeng. Preparation of ultra-fine explosive HMX and RDX using high-speed impinging streams[J]. *Journal of Beijing Institute of Technology*, 1999, 19(5): 120-124.

[86] 张小宁, 王卫民, 徐更光.高速撞击流技术制备炸药超细微粉的研究[J].火炸药学报, 1999(3): 2-4.
ZHANG Xiao-ning, WANG Wei-min, XU Geng-guang. Study on the preparation of ultrafine particle of explosive using the technology of high-speed impinging streams [J]. *Chinese Journal of Explosives and Propellants*, 1999(3): 2-4.

[87] 张小宁, 徐更光, 何得昌, 等.纳米级奥克托今超微颗粒制备技术研究[J].兵工学报, 2002, 23(4): 472-475.
ZHANG Xiao-ning, XU Geng-guang, HE De-chang, et al. A study on the preparation technology of nanometer ultra-fine HMX particle[J]. *Acta Armamentarii*, 2002, 23(4): 472-475.

[88] 陶鹏, 何得昌, 徐更光.高速撞击流技术制备超细RDX的研究[J].火工品, 2004(4): 23-25,30
TAO Peng, HE De-chang, XU Geng-guang. Study on the preparation of ultrafine RDX using the technology of high-speed-impinging streams[J]. *Initiators and Pyrotechnics*, 2004(4): 23-25,30.

[89] 何得昌, 周霖, 徐军培.纳米级RDX颗粒的制备[J].含能材料, 2006, 14(2): 142-143,150.
HE De-chang, ZHOU Lin, XU Jun-pei. Preparation of nanometer RDX particles[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2006, 14(2): 142-143,150.

[90] 何得昌, 周霖, 陈潜.分散剂在超细HMX制备中的应用[J].火工品, 2005(1): 33-34,1.
HE De-chang, ZHOU Lin, CHEN Qian. Application of dispersant on the preparation of nano-scale HMX [J]. *Initiators and Pyrotechnics*, 2005(1): 33-34,1.

[91] 何得昌, 陈潜, 谭峭.撞击流法制备超细HMX中撞击压力和次

数对颗粒度的影响[J]. 含能材料，2004,12(5)：300-301,255.
HE De-chang，CHEN Qian，TAN Zheng. The Effect of pressure and times of impinging on the particle size of superfine HMX by impinging method[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2004,12(5)：300-301,255.

[92] 陈潜，何得昌，徐更光，等.高速撞击流法制备超细HMX炸药[J]. 火炸药学报，2004，27(2)：23-25.
CHEN Qian，HE De-chang，XU Geng-guang，et al. Preparation of ultrafine particle of HMX explosive using the technology of high-speeding impinging streams[J]. *Chinese Journal of Explosives and Propellants*，2004，27(2)：23-25.

[93] 何得昌，郑波，谭峭.窄分布纳米级HMX的制备[J]. 含能材料，2004，12(1)：43-45.
HE De-chang，ZHENG Bo，TAN Zheng. Preparation of HMX with nanometer particle size and narrow particle distribution [J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2004，12(1)：43-45.

[94] 郑波，何得昌.窄分布纳米级HMX的制备及粒度分析[J]. 固体火箭技术，2003，26(4)：58-59.
ZHENG Bo，HE De-chang. Preparation and particle size analysis of narrow dis-tributed nano-scale HMX [J]. *Journal of solid Rocket Technology*，2003，26(4)：58-59.

[95] 魏田玉，李志华，刘巧娥，等.脉冲柱塞粉碎法制备超细RDX炸药[J]. 含能材料，2005，13(5)：57-58,5.
WEI Tian-yu，LI Zhi-hua，LIU Qiao-e，et al. Ultrafine RDX explosive prepared by pulse ram-type pulverization method[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2005，13(5)：57-58,5.

[96] 曾贵玉，刘春，赵林，等.高压超声破碎法制备微纳米TATB[J]. 含能材料，2015,23(8)：746-750.
ZENG Gui-yu，LIU Chun，ZHAO Lin，et al.Preparation of micro-nano TATB by high-pressure and ultrasonic breaking method[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2015，23(8)：746-750.

[97] 刘俊志，邹洁，左金，等.气流粉碎制备超细炸药的实验研究[J]. 航天工艺，2000(6)：24-27.
LIU Jun-zhi，ZOU Jie，ZUO Jin，et al. Experimental study on preparation of ultrafine explosives by air flow comminution [J]. *Aerospace Manufacturing Technology*，2000(6)：24-27.

[98] 刘俊志，左金，邹洁，等.气流粉碎分级制备超细火炸药的实验研究[J]. 航天工艺，2001 (4)：15-17,22.
LIU Jun-zhi，ZUO Jin，ZOU Jie，et al. Experimental study on preparation of ultrafine explosives by air flow crushing and grading[J]. *Aerospace Manufacturing Technology*，2001 (4)：15-17,22.

[99] 曾贵玉，聂福德，田野，等.气流粉碎法制备亚微米TATB粒子的研究[C]//全国纳米材料和技术应用会议.2001.
ZENG Gui-yu，NIE Fu-de，TIAN Ye，et al. Preparation of sub-micron TATB using airflow-smash [C]//National Conference on Nanomaterials and Technology Applications.2001.

[100] 曾贵玉，聂福德，张启戎，等.超细TATB制备方法对粒子结构的影响[J]. 火炸药学报，2003，26(1)：8-11.
ZENG Gui-yu，NIE fude，ZHANG Qirong，et al. The influence of preparation method on the particle structure of ultrafine TATB[J]. *Chinese Journal of Explosives and Propellants*，2003，26(1)：8-11.

[101] 曾贵玉，聂福德，王建华，等.高速气流碰撞法制备超细TATB粒子的研究[J]. 火工品，2003 (1)：1-3.
ZENG Gui-yu，NIE fude，WANG Jian-hua，et al. Preparation of ultrafine TATB particles by high-speed gas impacting method [J]. *Initiators and Pyrotechnics*，2003 (1)：1-3.

[102] Kleinschmidt E，Spaeth H. Crushing of solid high explosives [C]// International Annual Conference of ICT，1998：14.1-14.12.

[103] 刘杰.具有降感特性纳米硝胺炸药的可控制备及应用基础研究[D]. 南京：南京理工大学，2015.
LIU Jie. Controlled preparation of lower sensitivity characterized nanometer nitramine explosives and their applying basic research [D]. Nanjing：Nanjing University of Science and Technology，2015.

[104] 刘杰，曾江保，李青，等.机械粉碎法制备纳米HMX及其机械感度研究[J]. 火炸药学报，2012，35(6)：12-14.
LIU Jie，ZENG Jiang-bao，LI Qing，et al. Mechanical pulverization for nano HMX and study on its mechanical sensitivities [J]. *Chinese Journal of Explosives and Propellants*，2012，35 (6)：12-14.

[105] 刘杰，王龙祥，李青，等.钝感纳米RDX的制备与表征[J].火炸药学报，2012，35(6)：46-50.
LIU Jie e，WANG Long-xiang，LI Qing，et al. Preparation and characterization of insensitive nano RDX[J]. *Chinese Journal of Explosives and Propellants*，2012，35(6)：46-50.

[106] 刘杰，杨青，郝嘎子，等. 纳米ε-CL-20的制备及其感度研究[C]//中国科协年会——含能材料及绿色民爆产业发展论坛. 2014.
LIU Jie，YANG Qing，HAO Ga-zi，et al. Preparation and sensitivity study of nano-ε- CL-20[C]//China Association for Science and Technology Annual Meeting——Energetic Materials and Green Civil Explosive Industry Development Forum. 2014.

[107] 刘杰，姜炜，李凤生，等.纳米级奥克托今的制备及性能研究[J]. 兵工学报，2013，34(2)：174-180.
LIU Jie，JIANG Wei，LI Feng-sheng，et al. Preparation and study of nano octahydro-1，3，5，7-tetranitro-1，3，5，7-tetrazocine[J]. *Acta Armamentarii*，2013，34(2)：174-180.

[108] Liu J，Jiang W，Li F，et al. Effect of drying conditions on the particle size，dispersion state，and mechanical sensitivities of nano HMX[J]. *Propellants*，*Explosives*，*Pyrotechnics*，2014，39(1)：30-39.

[109] Liu J，Jiang W，Zeng J，et al. Effect of drying on particle size and sensitivities of nano hexahydro-1，3，5-trinitro-1，3，5-triazine[J]. *Defence Technology*，2014，10(1)：9-16.

[110] Liu J，Jiang W，Yang Q，et al. Study of nano-nitramine explosives：preparation，sensitivity and application [J]. *Defence Technology*，2014，10(2)：184-189.

[111] Guo X，Ou Y，Liu J，et al. Massive preparation of reduced-sensitivity nano CL-20 and its characterization[J]. *Journal of Energetic Materials*，2015，33：4-33.

[112] 王志祥.机械化学法制备HMX/TATB复合粒子及其性能研究[D]. 南京：南京理工大学，2016.
WANG Zhi-xiang. Preparation of HMX/TATB composite particles using a mechanochemical approach and its′ proformance study[D]. Nanjing：Nanjing University of Science and Technology，2016.

[113] 王卫民，赵晓利，张小宁.高速撞击流技术制备炸药超细微粉的工艺研究[J]. 火炸药学报，2001(1)：52-54.
WANG Wei-min，ZHAO Xiao-li，ZHANG Xiao-ning. Study of technology on the preparation of ultrafine particle of explosive

using the technology of high-speed impinging streams[J]. *Chinese Journal of Explosives and Propellants*, 2001 (1): 52-54.

[114] Huang B, Qiao Z, Nie F, et al. Fabrication of FOX-7 quasi-three-dimensional grids of one-dimensional nanostructures via a spray freeze-drying technique and size-dependence of thermal properties[J]. *Journal of Hazardous Materials*, 2010, 184(1-3): 561-566.

[115] Wuillaume A, Beaucamp A, David-Quillot F, et al. Formulation and characterizations of nanoenergetic compositions with improved safety [J]. *Propellants, Explosives, Pyrotechnics*, 2014, 39(3): 390-396.

[116] Brill T B, Tappan B C, Li J. Synthesis and characterization of nanocrystalline oxidizer/monopropellant formulations[J]. *Materials Resarch Society Symposium Proceedings*, 2003, 800: 47-54.

[117] Li J, Thomas B B. Nanostructured energetic composites of CL-20 and binders synthesized by sol gel methods[J]. *Propellants, Explosives, Pyrotechnics*, 2010, 31(1): 61-69.

[118] Bosma J C, Vonk P, Wesselingh J, et al. Which shape factor (s) best describe granules[J]. *Powder Technology*, 2004, 146 (1): 66-72.

[119] Cox E P.A Method of assigning numerical and percentage values to the degree of roundness of sand grains[J]. *Journal of Paleontology*, 1927, 1(3): 179-183.

[120] 徐瑞娟, 康彬, 黄辉, 等.HMX晶体颗粒球形度的定量表征[J]. 含能材料, 2006,12(4): 280-282.
XU Rui-juan, KANG Bin, HUANG Hui, et al. Quantitative characterization of HMX particle sphericity[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2006, 12(4): 280-282.

[121] Bowden F P, Yoffe Y D. Initiation and growth of explosion in liquids and solids [M]. Cambridge University Press, Cambridge, 1952.

[122] 吕春玲.主体炸药粒度及粒度级配与炸药冲击波感度和能量输出的实验与理论研究[D]. 太原: 华北工学院, 2001.
LÜ Chun-ling. Experimental and theoretical study on particle size and size gradation of main explosives and shock wave sensitivity and energy output of explosives [D]. Taiyuan: North China Institute of technology, 2001.

[123] Khasainov B A, Borisov A A, Ermolaev B S, et al. Two-phase visco-plastic model of shock initiation of detonation in high density pressed explosives[C]//Seventh Symposium (International) on Detonation. 1981.

[124] Zeman S, Yan Q L, Gozin M, Zhao F Q, Akštein Z. Thermal behavior of 1,3,5-trinitroso-1,3,5-triazinane and its melt-castable mixtures with cyclic nitramines[J]. *Thermochimica Acta*, 2015, 615: 51-60.

[125] Yoh J, Kim Y, Kim B, et al. Characterization of aluminized RDX for chemical propulsion[J]. *International Journal of Aeronautical and Space Sciences*, 2015, 16(3): 418-424.

[126] Yehya F, Chaudhary A K, Srinivas D, et al. Study of thermal decomposition mechanisms and low-level detection of explosives using pulsed photoacoustic technique[J]. *Applied Physics B*, 2015, 121(2): 193-202.

[127] Yang Z, Ding L, Wu P, et al. Fabrication of RDX, HMX and CL-20 based microcapsules via in situ polymerization of melamine-formaldehyde resins with reduced sensitivity [J]. *Chemical Engineering Journal*, 2015, 268: 60-66.

[128] Long Y, Chen J. Systematic study of the reaction kinetics for HMX[J]. *The Journal of Physical Chemistry A*, 2015, 119 (18): 4073-4082.

[129] Labarbera D A, Zikry M A. Heterogeneous thermo-mechanical behavior and hot spot formation in RDX-Estane energetic aggregates [J]. *International Journal of Solids and Structures*, 2015, 62: 91-103.

[130] Labarbera D A, Zikry M A. Dynamic fracture and local failure mechanisms in heterogeneous RDX-Estane energetic aggregates [J]. *Journal of Materials Science*, 2015, 50(16): 5549-5561.

[131] Fathollahi M, Mohammadi B, Mohammadi J. Kinetic investigation on thermal decomposition of hexahydro-1, 3, 5-trinitro-1, 3, 5-triazine (RDX) nanoparticles[J]. *Fuel*, 2013, 104 (9): 95-100.

[132] 邵颖惠, 刘文亮, 张冬梅, 等.全浸式真空安定性法研究固态HMX的热分解动力学[J]. 火炸药学报, 2012, 35(4): 33-36.
SHAO Ying-hui, LIU Wen-liang, ZHANG Dong-mei, et al. Study on thermal decomposition kinetics of solid HMX by continuous gasometric method[J]. *Chinese Journal of Explosives and Propellants*, 2012, 35(4): 33-36.

[133] Liu R, Zhou Z, Yin Y, et al. Dynamic vacuum stability test method and investigation on vacuum thermal decomposition of HMX and CL-20[J]. *Thermochimica Acta*, 2012, 537(3): 13-19.

[134] 刘芮, 尹艳丽, 张同来, 等.动态真空安定性试验方法研究(Ⅳ):HMX的热分解[J]. 含能材料, 2011, 19(6): 650-655.
LIU Rui, YIN Yan-li, ZHANG Tong-lai, et al. Dynamic vacuum stability test (DVST) method (IV): thermal decomposition of HMX[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2011, 19(6): 650-655.

[135] 尹艳丽, 杨利, 胡晓春, 等.动态真空安定性试验(DVST)方法研究(Ⅱ): RDX的热分解[J]. 含能材料, 2010, 18(4): 387-392.
YIN Yan-li, YANG Li, HU Xiao-chun, et al. Dynamic vacuum stability test (DVST) method (Ⅱ): thermal decomposition of RDX[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*),, 2010, 18(4): 387-392.

[136] 刘杰, 戎园波, 靳承苏, 等.基于临界电子激发能研究硝胺炸药纳米化降感机理[J]. 中国材料进展, 2017, 36(6): 420-424,441.
LIU Jie, RONG Yuan-bo, JIN Cheng-su, et al. Mechanism research for reducing sensitivity of nitramine explosive particles by nanocrystallization based on critical electronic excitation energy[J]. *Materials China*, 2017, 36(6): 420-424,441.

[137] Liu J, Ke X, Hao G, et al. Intuitionistic study on the critical decomposition energy of ammonium perchlorate by SEM[J]. *RSC Advances*, 2017, 7(79): 50121-50126.

[138] Dehm H C. Compositemodified double-base propellantwith filler bonding agent: US 4038115 A[P], 1977.

[139] 焦清介, 李江存, 任慧, 等.RDX粒度对改性双基推进剂性能影响[J]. 含能材料, 2007, 15(3): 220-223.
JIAO Qing-Jie, LI Jiang-cun, REN Hui, et al. Effect of RDX particle size on properties of CMDB propellants[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*), 2007, 15(3): 220-223.

[140] 王军, 谯志强, 杨光成, 等.以纳米粒子增强力学性能的高聚物粘接炸药及其制备方法: CN104649850[P], 2015.
WANG Jun, QIAO Zhi-qiang, YANG Guang-cheng, et al.

Polymer bonded explosives reinforced with nano particles and their preparation methods: CN104649850[P], 2015.

[141] 李宇翔，吴鹏，花成，等.微纳米HMX基PBX力学、导热性能及药片撞击感度[J]. 含能材料，2018，26(4)：334-338.
LIYu-xiang，WU Peng，HUA cheng，et al. Mechanical thermal conductive properties and tablet impact sensitivity of micro-nano-HMX based PBX[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2018，26(4)：334−338.

[142] 高康.超细CL-20的晶型控制与包覆配方设计研究[D]. 太原：中北大学，2016.
GAO Kang.Study on crystal types control and coating formula design of ultrafine CL-20[D]. Taiyuan：North Central University，2016.

[143] 徐瑞娟，康彬，黄辉，等.一种高品质含能晶体材料细颗粒制备方法：CN102320903[P]，2012.
XU Rui-juan，KANG Bin，HU Hui，et al. Preparation method of high quality energetic crystal material fine particles：CN102320903[P]，2012.

[144] Talawar M B，Agarwal A P，Gore G M，et al. Method for preparation of fine TATB (2-5 microm) and its evaluation in plastic bonded explosive (PBX) formulations[J]. *Journal of Hazardous Materials*，2006，137(3)：1848−1852.

[145] 荆肖凡.CL-20基低能起爆炸药技术研究[D]. 太原：中北大学，2014.
JING Xiao-fans.Technology of research CL-20 based explosive of low energy detonating[D]. Taiyuan：North Central University，2014.

[146] Lee K E，Braithwaite P C，Nicolich S，et al. Low-sensitivity explosive compositions：US6881283[P]，2005.

[147] Liu J，Jiang W，Yang Q，et al.Study of nano-nitramine explosives：preparation，sensitivity and application [J]. *Defence Technology*，2014，10(2)：184−189.

[148] Liu J，Bao Xiaoz，Rong Y，et al. Preparation of nano-RDX-based PBX and its thermal decomposition properties[J]. *Journal of Thermal Analysis and Calorimetry*，2017(3)：1−6.

[149] Liu J，Ke X，Xiao L，et al. Application and properties of nanometric HMX in PBX[J]. *Combustion Explosion and Shock Waves*，2017，53(6)：744−749.

[150] 肖磊，刘杰，郝嘎子，等.微纳米RDX颗粒级配对压装PBX性能影响[J]. 含能材料，2016，24(12)：1193−1197.
XIAO Lei，LIU Jie，HAO Ga-zi，et al.Effects of nano/micrometer RDX particle gradation on the property of PBX[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2016，24(12)：1193−1197.

[151] 靳承苏，肖磊，王庆华，等.微/纳米HMX颗粒级配对PBX性能的影响[J]. 含能材料，2017，25(11)：913−919.
JIN Cheng-su，XIAO Lei，WANG Qing-hua，et al. Effect of micro/nanometer HMX particle gradation on PBX properties[J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2017，25(11)：913−919.

[152] 戎园波，肖磊，王庆华，等.微/纳米HMX粒度级配对TNT基熔铸炸药性能的影响[J]. 火炸药学报，2018，41(1)：36−40.
RONG Yuan-bo，XIAO Lei，WANG Qing-hua，et al. Effect of micro/nanometer HMX gradation on the properties of TNT based castable explosives[J]. *Chinese Journal of Explosives and Propellants*，2018，41(1)：36−40.

[153] 宋伟冬，刘玉存，刘登程.起爆逻辑网络用挤注型传爆药研究[J]. 火工品，2010(4)：10−13.
SONG Wei-dong，LIU Yu-cun，LIU Deng-cheng. Study on the squeezing booster explosive used in the initiating logic network[J]. *Initiators and Pyrotechnics*，2010(4)：10−13.

[154] 艾进，李建军，陈建波，等.LLM-105基PBX炸药的热分解反应动力学[J]. 火炸药学报，2016，39(4)：37−41.
AI Jin，LI Jian-jun，CHEN Jian-bo，et al. Kinetics of thermal decomposition reaction of LLM-105 based PBX explosives[J]. *Chinese Journal of Explosives and Propellants*，2016，39(4)：37−41.

[155] Zhang J，Wu P，Yang Z，et al. Preparation and properties of submicrometer-sized LLM-105 via spray-crystallization method[J]. *Propellants*，*Explosives*，*Pyrotechnics*，2015，39(5)：653−657.

[156] 刘树浩，张景林，张俊，等.HMX的氟橡胶包覆技术及其撞击感度研究[J]. 中国安全生产科学技术，2011，7(6)：5−8.
LIU Shu-hao，ZHANG Jing-lin，ZHANG Jun，et al. Study on coated technology of HMX with FPM_{2602} and its impact sensitivity[J]. *Chinese Journal of Safety Science and Technology*，2011，7(6)：5−8.

[157] 梁逸群，张景林，姜夏冰，等.超细A_5传爆药的制备及表征[J]. 含能材料，2008，16(5)：515−518.
LIANG Yi-qun，ZHANG Jing-lin，JIANG Xia-bing，et al. Preparation and characterization of ultrafine A_5 propellant [J]. *Chinese Journal of Energetic Materials*(*Hanneng Cailiao*)，2008，16(5)：515−518.

[158] 谯志强，陈瑾，黄兵，等.一种安全环保型起爆药替代物及制备方法：CN102603442[P]，2012.
QIAO Zhi-qiang，CHEN Jin，HUANG Bing，et al. A safe and environment-friendly primer substitute and its preparation method.：CN102603442[P]，2012.

[159] 鲍国钢，朱长江，侯建华，等.一种高起爆感度变色导爆管：CN104803813[P]，2015.
BAO Guo-gang，ZHU Chang-jiang，HOU Jian-hua，et al. A high-initiation sensitivity color-changing detonating tube：CN104803813[P]，2015.

[160] 张亚俊.超细RDX在CMDB推进剂中的应用研究[C]//中国宇航学会固体火箭推进第22届年会.2005，3.
ZHANG Ya-jun. Application of ultrafine RDX in CMDB propellant[C]//China Astronautical Society Solid Rocket Propulsion 22nd Annual Meeting. 2005，3.

[161] Liu J，Hao G，Rong Y，et al. Application and properties of nano-sized RDX in CMDB propellant with low solid content[J]. *Propellants*，*Explosives*，*Pyrotechnics*，2017，43(2)：144−150.

[162] Menke K，Bohnlein-Mauss J，Schmid H，et al. Solid propellant based on phase-stabilized ammonium nitrate：US5596168[P]. 1997.

[163] 宋琴，顾健，尹必文，等.降低固体推进剂高压压强指数的配方：CN106336334[P]，2017.
SONG Qin，GU Jian，YIN Bi-wen，et al. Formulation for lowering high pressure index of solid propellant：CN106336334[P]，2017.

[164] 官震.Al/MoO_3含能半导体桥的点火与起爆技术研究[D]. 南京：南京理工大学，2016.
GUAN Zhen. Investigation on ignition and initiation techniques of Al/MoO_3 energetic semiconductor bridge[D]. Nanjing：Nanjing University of Science and Technology，2016.

[165] 沈金朋，杨光成，谯志强，等.高能微点火芯片及其制备方法和使用方法：CN105258580[P]，2016.

SHEN Jin-peng, YANG Guang-cheng, QIAO Zhi-qiang, et al. High-energy micro-ignition chip and its preparation and use method: CN105258580[P], 2016.

[166] An C, Xu S, Zhang Y, et al. Nano-HNS particles: mechano-chemical preparation and properties investigation[J]. *Journal of Nanomaterials*, 2018(4): 1-7.

Advances in Micro-nano Energetic Materials

LI Feng-sheng, LIU Jie

(*National Special Superfine Powder Engineering Research Center of China, School of Chemical Engineering, Nanjing University of Science and Technology, Nanjing* 210094, *China*)

Abstract: Micro-nano energetic materials exhibit excellent properties and good application results due to their small size effect, crystal perfection effect, high surface energy and high surface activity. In this paper, the current advances in the recrystallization technologies and pulverization technologies used in the preparation of micro-nano energetic materials at present, and the drying technologies, characterization methods of particle size and morphology, mechanisms of sensitivity changed with particle size, application directions and effect etc. of micro-nano energetic materials were summarized based on the related research work of scholars both at home and abroad. It is pointed out that micro-nano energetic materials in the future should focus on the research work of strengthening basic theory, simulation, functional mechanism of application, engineering magnification and practical application etc. of micro-nano energetic materials, so that micro-nano energetic materials can be transferred into engineering applications as soon as possible, so as to accelerate the development of high-energy solid rocket propellants, composite explosives, gun propellants as well as pyrotechnics, and improve their performances.

Key words: micro-nano; energetic materials; preparation; characterization; mechanism; application

CLC number: TJ55; O64 **Document code**: A **DOI**: 10.11943/CJEM2018280

读者·作者·编者

《含能材料》“损伤与点火”专栏征稿

含能材料的损伤特征与点火过程有密切的联系,炸药、推进剂的内部损伤及其对力学特性、安全特性和点火行为的影响规律受到了含能材料学界的高度重视,为推动这一重要研究方向的学术交流,本刊特设立“损伤与点火”专栏。专栏主要征集炸药、推进剂等含能材料的损伤观测与多尺度表征技术、含损伤的本构方程、准静态与动态损伤演化规律、损伤与破坏的宏(细)观模式、损伤对起爆、爆炸、爆轰成长以及非冲击起爆行为的影响等方向的原创性研究论文。来稿请注明“损伤与点火”专栏。

《含能材料》编辑部