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## 一种含铝炸药压缩力学性能和本构关系研究

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**摘要:** 对某含铝炸药进行了准静态和动态压缩实验, 得到了不同初始密度的材料在不同应变率下的应力-应变曲线; 曲线表明, 材料的压缩强度随初始密度及加载应变率的增大而增加; 初步建立了材料在不同初始密度、不同应变率下的本构模型, 拟合曲线与实验曲线吻合较好, 对该炸药不同密度下的力学行为特征和应变率效应得到了较为系统的认识。

**关键词:** 固体力学; 含铝炸药; 本构关系; 应变率效应

**中图分类号:** O338; TJ55

**文献标识码:** A

### 1 引言

炸药中添加热焓较高的金属粉末, 利用金属燃烧的热量提升炸药的爆热, 可以有效地提高混合炸药的总能量, 增强爆炸效应。将其应用到战斗部装药可以显著提高破片的冲量, 提高水下兵器战斗部的气泡能。在众多的金属添加剂中, 由于铝的氧化热和活性较高, 且来源广泛、价格低廉, 含铝炸药成为军用混合炸药的重要系列。

随着对含能材料安全性的研究深入, 人们逐渐关心含能材料的力学性能, 尤其是动态力学性能。G. Scholtes等<sup>[1]</sup>研究了温度为 $-60 \sim 60 \text{ }^\circ\text{C}$ , 应变率为 $0.001 \sim 5 \text{ s}^{-1}$ 的PBX炸药的热学与力学损伤, 同时用光学显微镜和扫描电镜观察了冲击加载后的试样, 建立了描述损伤的机理认识和数学模型, 获得了被测材料的力学本构, 并用于Autodyn计算软件。吴会民等<sup>[2]</sup>对一种PBX炸药和压装B炸药进行了准静态和动态压缩实验, 得到了两种炸药在不同应变率下的应力应变曲线, 建立了两种炸药含应变率效应的本构方程。目前对于含铝炸药的研究还主要集中在配方和爆轰性能的分析上<sup>[3,4]</sup>, 对涉及其力学性能的研究较少。由于含铝炸药的力学性能对含铝炸药战斗部设计和安全性分析有着重要的基础作用, 为此本实验研究了一种压装含铝炸药的力学性能对压装密度及加载应变率的响应规律。

### 2 实验

含铝炸药组分: 76%的RDX, 20%的铝粉和4%的

粘结剂。达到最佳爆轰性能的理想密度 $1.88 \text{ g} \cdot \text{cm}^{-3}$ , 冲击感度不小于5 GPa。试样为模具压制成形, 出于实验安全考虑, 试样密度为 $1.5, 1.6, 1.7 \text{ g} \cdot \text{cm}^{-3}$ 。

静态实验采用长春试验机厂生产的WDW-100型静态试验机, 加载速度为 $0.01 \text{ m} \cdot \text{min}^{-1}$ , 试样尺寸为 $\Phi 20 \text{ mm} \times 20 \text{ mm}$ 。

动态实验采用SHPB实验技术, 应变率为450, 600, 800  $\text{s}^{-1}$ , 试样尺寸为 $\Phi 15 \text{ mm} \times 8 \text{ mm}$ 。实验杆材料为LC4铝, 直径20 mm子弹长150 mm, 入射杆长200 mm, 透射杆长100 mm。应变测试采用自行研制的KD205-1A超动态应变仪, 采集实验信号用TDS3054 B数字存储示波器。应用入射波整形技术, 以保证试样处于常应变率加载状态。图1是SHPB实验典型的原始波形, 其中ch1记录入射波和反射波, ch2记录透射波。从图中的波形可以看出在试样破坏之前, 反射波基本为一个平台, 意味着实验中试样破坏前为常应变率加载。

为防止实验意外爆炸对人员及仪器造成伤害, 设计了由保护盒和保护挡板组成的保护装置, 如图2所示。

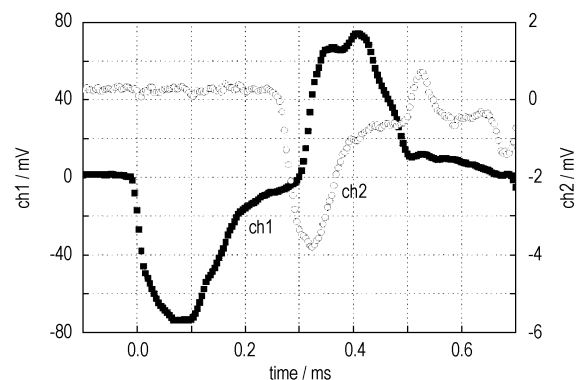


图1 SHPB测试原始曲线

Fig. 1 Oscilloscopic records of a SHPB test

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### 3 炸药材料应力-应变曲线

由于对于低波阻抗试样,反射波十分接近入射波,两波相加的来计算入射端面应力时,测试时的误差可能会对结果有很大的影响,以至于计算结果完全不可用。为此,本实验采用简化的三波方法来处理<sup>[5]</sup>,其应变计算采用三波法,应力则仅用透射波计算。

图 3 给出了某压装含铝炸药在不同应变率(0.008 ~ 800 s<sup>-1</sup>)下的应力应变曲线。压缩强度如表 1 所示,可以看出该材料压缩强度对初始密度及应变率都比较敏感。

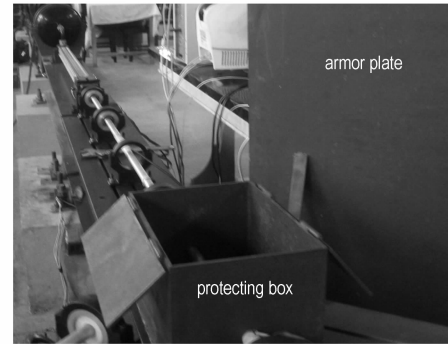


图 2 保护装置图

Fig. 2 Photograph of protecting system

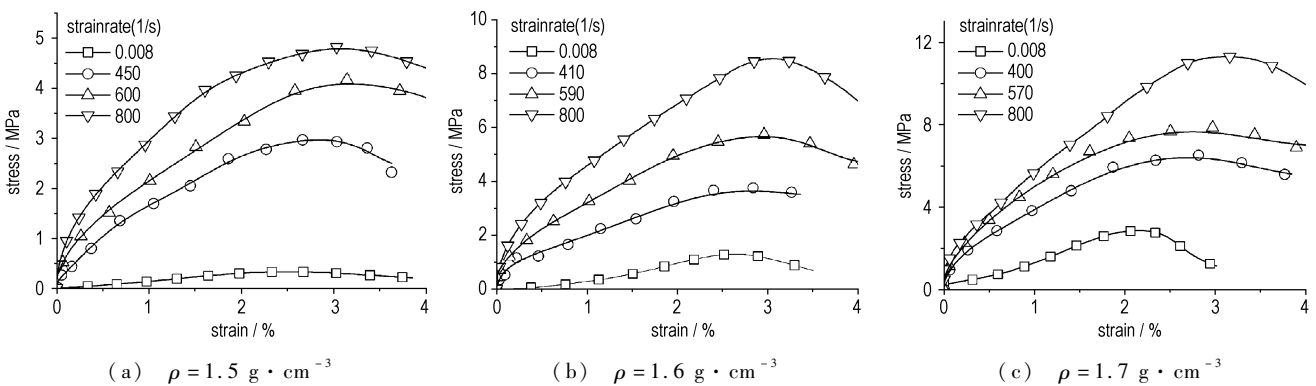


图 3 不同应变率下应力应变曲线

Fig. 3 Compressive stress-strain curves at different strain rates

表 1 不同密度及应变率下的压缩强度

Table 1 Failure stresses at different densities and strain rates

density $\rho/g \cdot cm^{-3}$	loading strainrate $\epsilon/s^{-1}$	experimental failure stress $\sigma_b/MPa$	expected failure stress $\sigma_b^*/MPa$
1.50	0.008	0.384	0.382
1.53	410	3.039	3.116
1.53	620	4.209	4.447
1.51	780	4.859	5.082
1.62	0.008	1.337	1.283
1.59	410	3.770	3.995
1.60	590	5.748	5.540
1.65	800	8.425	8.396
1.70	0.008	2.848	2.872
1.70	400	6.531	6.644
1.69	570	7.879	7.869
1.72	800	11.33	11.35

Note: The  $\sigma_b$  is expected by Equation (2).

将应力应变曲线应力归一化,令归一化的应力如下:

$$\bar{\sigma} = \sigma / \sigma_b \quad (1)$$

其中, $\sigma_b$ 为试样的压缩强度, $\sigma$ 为试样的压缩应力, $\bar{\sigma}$ 为归一化的压缩应力。如图 4 所示,将应力归一化后不同密度、不同加载应变率下材料应力应变曲线基本重合。

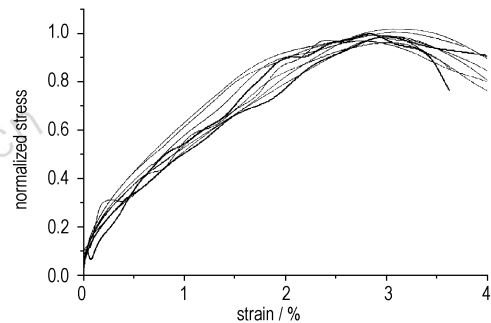


图 4 应力归一化后应力应变曲线

Fig. 4 Stress-strain curves after stress normalized

### 4 本构关系研究

该含铝炸药是一种通过高分子材料粘结成的颗粒增强型复合材料,材料应力应变曲线有较强的非线性特征。参考吴会民等<sup>[2]</sup>的研究工作,同时考虑到材料初始密度不同对压缩强度的影响,及其与应变率的交互作用,基于实验本构曲线的特性进行以下本构模型研究。

本构关系的拟合分四步走,首先按公式(1)将应力应变曲线应力归一化。

第二步,拟合压缩强度与试样初始密度及加载应变率的关系如下:

$$\sigma_b = \sigma_0 \cdot \exp\left(\alpha\left(1 - \frac{\rho}{\rho_0}\right) + \beta \cdot \left(\left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right) - 1\right) + \gamma \cdot \left(1 - \frac{\rho}{\rho_0}\right) \cdot \left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right) - 1\right) \cdot (A\varepsilon + B\varepsilon^n) \quad (2)$$

其中,  $\rho_0$  为材料理想密度  $1.88 \text{ g} \cdot \text{cm}^{-3}$ ,  $\varepsilon_0$  取  $1 \text{ s}^{-1}$ ,  $\sigma_0$  为理想密度试样加载应变率为  $1 \text{ s}^{-1}$  下的压缩强度,  $\alpha$  为密度影响因子,  $\beta$  为应变率影响因子,  $\gamma$  为交叉影响项。采用遗传算法拟合得到结果:  $\sigma_0 = 14.24 \text{ MPa}$ ,  $\alpha = -17.04$ ,  $\beta = 1.329\text{E}-2$ ,  $\gamma = -3.851\text{E}-2$ 。基于公式(2),表1给出了不同密度和应变率下计算值与实验值的比较。结果表明,公式(2)对所测试的材料性能给出了较好的预测。

第三步,拟合应力归一化后的应力应变关系如下:

$$\bar{\sigma} = A\varepsilon + B\varepsilon^n \quad (3)$$

上式中第一项表示弹性段特征,第二项表示粘塑性段特征。且由试验曲线可以近似认为,  $A$ 、 $B$ 、 $n$  是反映材料本质特性的参数,与初始密度及加载应变率无关。拟合得:  $A = 130.8$ ,  $B = 314.4$ ,  $n = 1.325$ 。

为了得到本构曲线,最后将(2)式代入应力归一

化后的应力应变曲线,得到本构关系如下:

$$\sigma = \left[ \sigma_0 \cdot \exp\left(\alpha\left(1 - \frac{\rho}{\rho_0}\right) + \beta \cdot \left(\left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right) - 1\right) + \gamma \cdot \left(1 - \frac{\rho}{\rho_0}\right) \cdot \left(\frac{\dot{\varepsilon}}{\varepsilon_0}\right) - 1\right) \right] \cdot (A\varepsilon + B\varepsilon^n) \quad (4)$$

图5给出了该压装含铝炸药的本构关系拟合曲线,从拟合情况看,动态情况下,拟合曲线与实验曲线吻合较好,静态的情况吻合不太一致,这是由于在采用(3)式拟合时忽略了应变率对参数  $A$ 、 $B$ 、 $n$  的影响。

## 5 结论

研究表明,压缩应力随着初始密度和加载应变率的增加而增加;由于高聚物基体的非线性,材料整体表现为非线性,但在应力归一化后,不同加载条件下非线性特征相似;建立的本构模型能较好的描述材料的力学行为。拟合了材料在不同初始密度、不同加载应变率下的压缩强度,并预测理想密度下材料的压缩强度,为含铝炸药战斗部的设计及安全性分析提供了初步的参数。

进一步的工作可以围绕该本构关系的应用方面展开,如将其加入商用计算软件的可能性。

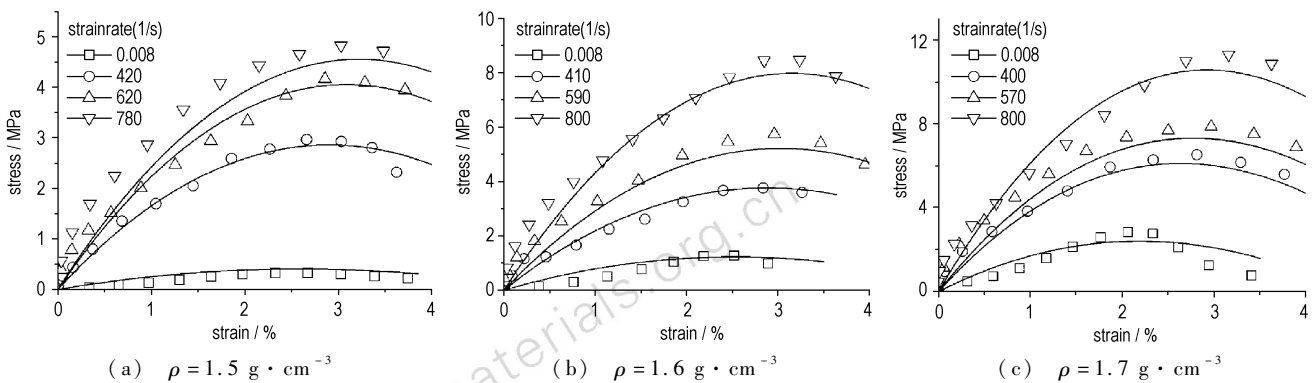


图5 不同应变率下本构关系拟合

Fig. 5 Constitutive curves fitted at different strains

## 参考文献:

- [1] Scholtes G. Thermal and mechanical damage of PBX's proceedings [A]. 12th International Detonation Symposium [C], 2002.
- [2] 吴会民, 卢芳云. 三种含能材料力学行为应变率效应的实验研究 [J]. 含能材料, 2004, 12(4): 227-230.  
WU Hui-min, LU Fang-yun. Experimental studies on strain-rate effects of mechanical behaviors of energetic materials [J]. *Chinese Journal of Energetic Materials (Hanneng Cailiao)*, 2004, 12(4): 227-230.
- [3] 苗勤书, 徐更光, 王廷增. 铝粉粒度和形状对含铝炸药性能的影响 [J]. 火炸药学报, 2002, 25(2): 4-8.  
MIAO Qin-shu, XU Geng-guang, WANG Ting-zeng. Mechanism analy-
- [4] Michael N Makhov, Vitaly I Arkhipov. Evaluation of the acceleration ability of aluminized high explosives [A]. 13th Proceedings of Detonation Symposium [C], 2006.
- [5] 宋力, 胡时胜. SHPB 数据处理中的二波法与三波法 [J]. 爆炸与冲击, 2005, 25(4): 368-372.  
SONG Li, HU Shi-sheng. Two-wave and three-wave method in SHPB data processing [J]. *Explosion and Shock Wave*, 2005, 25(4): 368-372.

sis of the influence of Al shape and size on the detonation properties of aluminized explosives [J]. *Chinese Journal of Explosives & Propellants*, 2002, 25(2): 4-8.

## Mechanical Behavior and Constitutive Model of Pressed Aluminized Explosive

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**Abstract:** Compressive behaviors of a pressed aluminized explosive with different densities ( $1.5, 1.6, 1.7 \text{ g} \cdot \text{cm}^{-3}$ ) were investigated experimentally by split Hopkinson pressure bars (SHPB) and hydraulic testing machine at different strain-rates (ranged from  $0.008 \text{ s}^{-1}$  to  $800 \text{ s}^{-1}$ ) respectively. Nonlinear stress-strain curves at different strain rates were obtained. The results show that the mechanical behaviors of the aluminized explosive is obviously rate-dependent, and the corresponding failure stresses become higher if the original density or loading strain rates rise. A constitutive relation was established base on the experimental curves.

**Key words:** solid mechanics; aluminized explosive; constitutive model; strain rate effect

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## Characteristic of the Thermobaric Explosive Contained Aluminum Powders

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**Abstract:** A thermobaric explosive containing aluminum powder shaped flake and many physic-chemical parameters' testing courses of the fuel were mainly introduced. The energy contained in fuel was calculated, the energy releasing efficiency of fuel was tested in different environment, and the fireball's expanding characteristic and shockwave's removing process were studied. The results show that the fuel's energy density is  $16.11 \text{ MJ} \cdot \text{kg}^{-1}$  theoretically, about 4 times of TNT-equivalency. The energy releasing rate of the aluminum flakes in the fuel is fast, and the released energy enhances the shockwave immediately when the shockwave is born and spreads. The fuel is safe in using and depositing. The capacity of the fuel's anti-loading is identified well after impact test and shooting test in large caliber fire-guns, and also show that the fuel is safe under the overload by  $1.7 \times 10^5 \text{ m} \cdot \text{s}^{-2}$ . The fuel's stability is adopt to the large caliber fire-guns' shooting condition.

**Key words:** applied chemistry; thermobaric fuel; explosion; aluminum flake

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## High-speed Liquid Jet Driven by Burned Gas of Gas Generating Compositions

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**Abstract:** A new spray device is presented in the paper. Its power source is burned gas produced by combustion of gas generation compositions. High-speed photography was used in the experiments. Atomization processes of spiral jet spray nozzles is studied under five different charge quantities (30 g, 40 g, 50 g, 70 g, 90 g) of gas generator. Experimental results show, the atomizing effect of jet can be improved with increasing charge quantity of the main propellant grains. When charge quantity of gas generator is more than 50 g, the atomizing effect of jet is preferable.

**Key words:** fluid mechanics; gas generator; spiral jet spray nozzle; high-speed photography