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Influence Rule of End Face Friction on Static Compressive Strength of Polymer Bonded Explosive（PBX）

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Abstract：To study the quasi-static compression response behavior of polymer bonded explosive（PBX）under different end face friction conditions，a typical casting PBX explosive was selected as the research object，and the quasi-static compression tests were carried out under three kinds of end face friction conditions：molybdenum disulfide lubrication，dry friction，and grease lubrication. The load-displacement curves were measured by using electronic universal material testing machine. Based on the isotropic elastic theory，the friction mechanism of the end face was preliminarily discussed by the energy conservation method. Results show that the static failure strain is closely related to the friction coefficient. Under the same friction conditions，the material with viscoelastic properties，high Poisson's ratio，great axial strain and small length-diameter ratio has an obvious end face friction effect in the static compression test.

Key words：polymer-bonded explosive（PBX）；end surface friction effect；static compression；law of the energy conservation

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1 Introduction

In recent years，due to the stronger protections for armors，weapons like kinetic energy penetrators and earth penetrators are facing increasingly harsh operational conditions，and they are required to have good mechanical properties. While the traditional fused explosives（TNT，2，4，6-trinitrotoluene）have such disadvantages as poor strength，toughness，and vulnerability to brittle fracture，they cannot fully meet the requirements of weapons in the new era[1-5]. Therefore，the polymer-bonded explosives（PBXs）are used as a substitute for early TNT fused explosives. When subjected to a force，the PBXs can deform greatly because of the relatively high inert additive in it，and it can store and consume parts of the impact energy in the binder during high-speed collisions. Therefore，the external forces which the main explosive particles in the mixed explosive undergo are greatly reduced，so the PBXs have a strong ability to withstand overloads. That is the reason that the mechanical properties and responses of PBXs in complex environments have been a hot topic in the field of energetic materials.

TANG Ming-feng[6-7] has used material testing machines to obtain the cyclic loading and unloading stress-strain curves for RDX（1，3，5-trinitrohexahydro-1，3，5-triazine）based casting PBXs. ZHOU Hong-ping and her partners[8-10] have used the uniaxial tensile tests and tensile creep tests to analyze the influence of temperature on the mechanical properties of casting PBXs. Belmas and his partners[11] have studied the TATB-based press-packed PBXs and

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found that there are differences in the failure mechanisms under different loads, and the mechanical properties are different under the tensile loading and compressive loading. Usually, the results of their static compression tests cannot precisely reflect the one-dimensional stress constitutive relationship of the material for the reason that the end surface friction effect destroys the local one-dimensional stress state. However, it is very difficult to accurately describe the friction effect[12-14]. At present, there are no reports about the test results of the friction effect of the end face by applying the static compression test method.

In our static compression test, a typical casting PBX is selected, and tested under the conditions of molybdenum disulfide lubrication, dry friction, and grease lubrication. At the same time, based on the theory of isotropic elasticity, the principal factors affecting the friction effect on the end face are analyzed using the energy conservation method.

2 Static Compression Test

The quasi-static experiment in this paper is conducted by a INSTRON5582 electronic testing machine in the Materials Physics and Mechanics Performance Laboratory, which belongs to the Institute of Chemical Materials of the Chinese Academy of Sciences. In the experiments, the loading speed w ($\mathrm{mm \cdot min^{-1}}$) is controlled by the central console. The loading force F(kN) and displacement s(mm) during the loading process are obtained respectively by a pressure sensor and an extensometer. The F-s curve can be observed in real time through the display device. According to the output data, the corresponding strain rate e, engineering strain Q, and engineering stress ε can be obtained from equations (1) to (3):

$$\dot{\varepsilon} = \frac{w}{60L_{\mathrm{s}}} \tag{1}$$

$$\sigma = \frac{F}{A_{\mathrm{s}}} = \frac{4}{\pi} \cdot \frac{F}{D_{\mathrm{s}^2}} \tag{2}$$

$$\varepsilon = \frac{s}{L_{\mathrm{s}}} \tag{3}$$

Where D_{s} and L_{s} are the diameter and thickness of the test piece respectively, and the unit is taken as mm.

The PBX consists of 1,3,5,7-tetranitro-1,3,5,7-tetrazocane(HMX), Al, ammonium perchlorate (AP), and hydroxyl-terminated polybutadiene (HTPB). The kneading-vacuum casting-curing process is adopted. Using this method, the main explosive particles are coated with binders and other additives and then casted and cured at a certain temperature. The sample of explosives is a Φ20 mm×20 mm grain, the density is 1.65 $\mathrm{g \cdot cm^{-3}}$. According to the test method of GJB 772A-1997, the quasi-static compression test is conducted under the conditions of room temperature (23 ℃), 55% RH and loading speed 0.5 $\mathrm{mm \cdot min^{-1}}$ (the corresponding strain rate is $4.17 \times 10^{-4}\ \mathrm{s^{-1}}$).

3 Analysis of Test Results

Casting PBXs have the characteristics of soft material and the ability of large deformation. Because the casting PBX consists of a large amount of polymer binders and is made by the casting process, it represents the viscoelasticity of the binder rather than the brittleness of the explosive crystals. It features low strength, low modulus and a larger critical strain in terms of macroscopic performance. Due to the viscoelastic effect of PBXs, the frictional effect of the end face during loading will have a great impact on the stress state of the sample. This requires maximum elimination of frictional effects between the sample face and the indenter. For PBXs, it is common to use lubricants including petrolatum, molybdenum disulfide, grease and vacuum grease. Through studies and comparisons, it is found that the grease has better lubrication effect on casting PBX. The grease-lubricated PBX sample maintains cylindrical until the end of the loading and there is no obvious bulging, indicating that the sample is in a good and evenly deformed state, as shown in Fig.1.

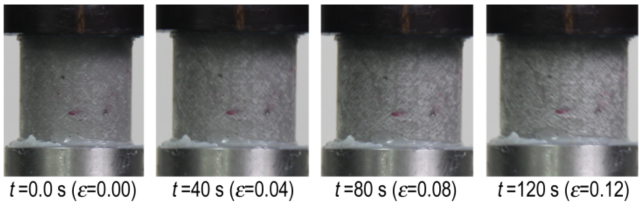


Fig.1 Photos of PBX deformation at different time

Tests have been performed under three kinds of end friction conditions, including molybdenum disulfide lubrication, dry friction and grease lubrication. The corresponding stress-strain curves have been calculated from the PBX load-displacement curves measured under different end face friction conditions, as shown in Fig.2.

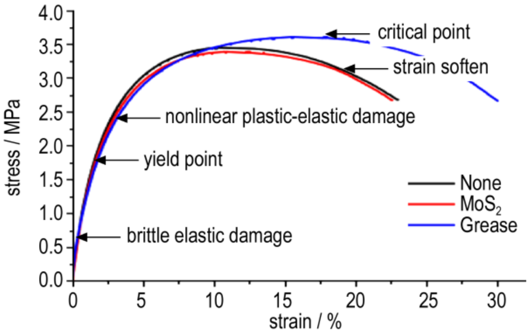


Fig. 2 Typical stress-strain curves of PBX under different end-face friction conditions

The definition of each phase of the stress-strain curve and the corresponding characteristic points are shown in Fig. 2. It can be seen that the stress-strain curve of PBX can be divided into three phases: the linear elastic phase, the strengthening phase, and the strain-softening phase. The mechanical properties of the PBX under quasi-static compression conditions are described using the elastic modulus, yield limit, compressive strength, and the strain corresponding to the compressive strength (or called critical strain, failure strain, etc.). The same conclusion can also be drawn from the stress-strain curve under different lubrication conditions. There are greater compressive strength and failure strain in the actual uniaxial compression state than that of where the friction effect exists, and in particular, the failure strain is a half of that, as shown in Fig.3 and Table 1. The low friction coefficient means the high static failure, and the end face with grease lubrication has the highest static failure(15.84%).

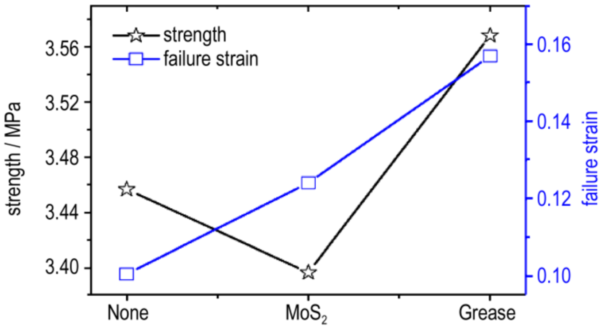
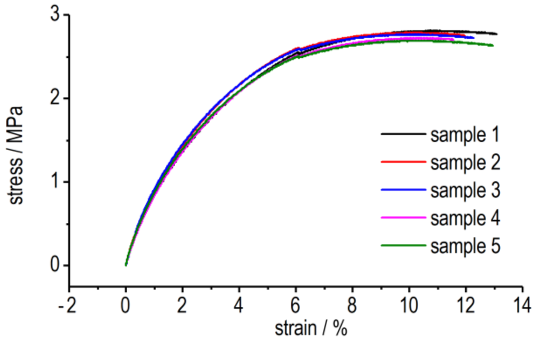


Fig. 3 Compressive strength and failure strain of PBX under different friction conditions

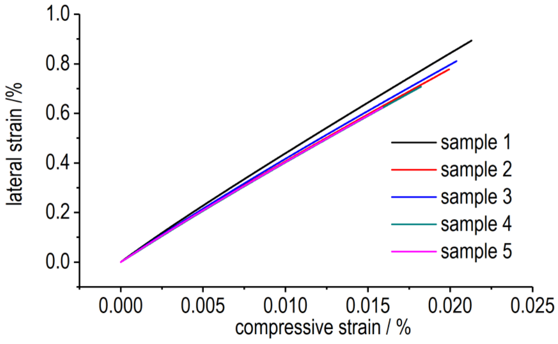
Table 1 Compressive strength and failure strain under different end friction conditions

lubricating way	none	MoS_2	grease
strength / MPa	3.457	3.397	3.523
failure strain / %	10.05	12.41	15.84

The results of the obtained compression tests are shown in Fig. 4 and we can find that the strain-stress curve(Fig.4a) of the PBX has an obvious nonlinearity at the initial stage, and there is no obvious yield point, and the lateral strain-compressive



a. strain-stress curves



b. compressive strain-lateral strain curves

Fig.4 The results of compression tests strain curve is straight. The elastic modulus, compressive strength, failure strain and Poisson ratio of materials under this experimental condition are shown in Table 2. It can be seen that the PBX has the characteristics of low modulus and low strength, which can produce large deformation after loading. It shows different viscoelastic characteristics with that of pressed explosive.

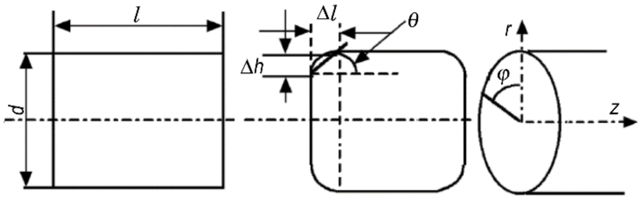
Table 2 Quasi-static compressive mechanical properties of PBXs

mechanical parameters	modulus of elasticity / MPa	break strength / MPa	compression strain / %	Poisson ratio
number	146	2.759	10.4	0.41

4 Mechanism of Friction Effect on The End Face

Based on the theory of isotropic elasticity, the mechanism of end face friction effect in static compression test is preliminarily discussed using the energy conservation method. Fig.5 shows the deformation process of the sample when there is end friction, the sample used in the experiment is cylindrical, thus cylindrical coordinates are used here. The length of the original sample is expressed in l, the diameter in d, and the bulk volume in Ω. Based on Fig.5b, it is known that the deformation of the sample is no longer uniform when there is end friction. Because of the friction at the end, the stress in the sample is very complex, and there are multiple stress components, and it does not meet the one-dimensional assumption. In order to help with the analysis, the following simplified assumptions are made.

(1) During the deformation process, only one area near the end face is affected by the end friction, which is called the uneven deformation zone. Here the width is Δl and the bulk volume is Ω'; and the area between l and $2\Delta l$ is the uniform deformation one.



a. original specimen **b.** transmuted specimen **c.** coordinate

Fig.5 Deformation with end face friction

(2) In the uneven deformation area, only axial stress and end shear force are considered. It is assumed that the axial stress at the end surface is $\overline{\sigma_z}$, which is the stress measured in the experiments. And the axial stress in the Δl is $\sigma_0\left(=E\varepsilon_z\right)$, which is the real one dimensional axial stress in the sample when there is no end friction. At the same time, it is assumed that the shear force $\tau_{r\phi}$ caused by the end friction is uniformly distributed in the whole Δl, which is a constant, and $\tau_{r\phi}=\mu\overline{\sigma_z}$.

(3) During the static compression experiment, the heat exchange between samples deformation and outside is not considered, and it is considered an adiabatic process. Part of the work done by external force will become kinetic energy and the other will become strain energy.

(4) For the same material, the kinetic energy of the sample is equal under different end face friction conditions. As shown in Fig.6, in the experimental results of material samples with obvious friction effect at the end faces, the energy in the sample is ΔE more than that of under the lubrication condition when there is face friction within the same strain increment $\Delta\varepsilon$. According to the hypothesis three, it can be considered that because of the friction of the end faces, the friction force does work on the sample, which results in the increase of the kinetic energy and strain energy in it. Because there is the same constant strain rate loading for the same material sample in the experiment, and it is assumed that the stress state of homogeneous deformation zone is the same as that of under lubrication, and the uneven deformation area is only near the end face with a small area, we neglect the change of kinetic energy caused by the change of the sample's particle velocity in heterogeneous deformation zone. It is considered that the kinetic energy of the sample is equal under different end face friction conditions, and the

work done by the friction force at the end face is all transformed into the strain energy of the sample.

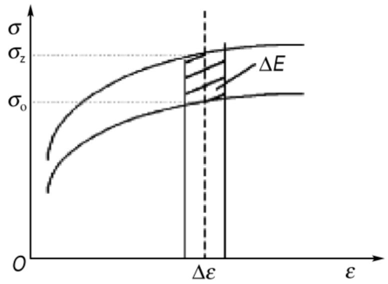


Fig.6 Energy schematic diagram of end face friction

In the case of face friction, the strain energy U stored inside the sample is composed of two parts: one is axial strain energy provided by axial strain $\varepsilon_{z,}$ U_ε; the other is the shear strain energy induced by shear strain energy $\gamma_{r\phi}$, which is provided by the shear force $\tau_{r\phi}$ from the end face friction, U_γ. $U_\gamma=\Delta E$, and the strain energy in the sample can be written as:

$$U = U_\varepsilon + U_\gamma \tag{4}$$

$$U = \iiint_\Omega \frac{1}{2}\overline{\sigma_Z}\varepsilon_Z \,\mathrm{d}\Omega$$

$$U_\varepsilon = \iiint_\Omega \frac{1}{2}\sigma_0\varepsilon_Z \,\mathrm{d}\Omega \tag{5}$$

$$U_\gamma = 2\iiint_{\Omega'} \frac{1}{2}\tau_{\gamma\phi}\gamma_{\gamma\phi}\,\mathrm{d}\Omega'$$

According to the theory of linear elasticity:

$$\gamma_{r\phi} = \frac{\tau_{r\phi}}{G} = \frac{2\mu(1+\nu)\overline{\sigma_z}}{E} \tag{6}$$

In the formula, G is the shear modulus of the material, E is the modulus of elasticity of material, ν refers to the Poisson's ratio for material. In the inhomogeneous deformation zone, we assume that the deformation is small:

$$\tan\theta = \gamma_{r\phi} \tag{7}$$

The radial deformation of end faces is neglected when end friction occurs:

$$\tan\theta = \frac{\Delta h}{\Delta l} = \frac{\nu\varepsilon_z d}{2\Delta l} \tag{8}$$

It can be obtained that:

$$\overline{\sigma_z}\left\{1 - \frac{\mu\nu d}{3l}\left[1 + (1+\nu\varepsilon_z) + (1+\nu\varepsilon_z)^2\right]\right\} = \sigma_0 \tag{9}$$

The formula (9) is derived from the theoretical analysis of the frictional effect of the end face in the static compression experiment. From the formula (9), it can be seen that the influence of the friction effect on the end face is greatly related to the material properties, such as the friction coefficient μ and Poisson's ratio v of material. The length to diameter ratio l/d and the axial strain ε_z in experiment are the main influencing factors. For the same material sample, the friction coefficient at the end faces is the decisive factor of the friction effect when the end face friction conditions are different. For samples of different material properties, if the Poisson's ratio of a material is large, the friction coefficient between the end faces is large, so does the axial strain. However, when the length to diameter ratio of sample is small, the friction effect of the material will be greater in the static compression test.

5 Conclusions

The quasi-static compression experiments of PBX were carried out through a material testing machine. Based on the isotropic elasticity theory, the energy conservation method was applied to discuss the mechanism of the end face friction.

(1) Due to the lubricated sample with grease, the frictional effect of the end face was eliminated, and the one-dimensional loading was realized.

(2) The low friction coefficient resulted to the high static failure, and the end face with grease lubrication had the highest static failure as 15.84%.

(3) Under the same friction condition, the material with viscoelastic properties, large Poisson's ratio, large axial strain and small length to diameter ratio has an obvious friction effect in the static compression experiment.

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端面摩擦对高聚物粘接炸药(PBX)静态压缩强度的影响规律

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摘　要： 为研究不同端面摩擦条件下的高聚物粘接炸药(PBX炸药的准静态压缩响应行为，选取一种典型的浇注PBX炸药作为研究对象，在二硫化钼润滑、干摩擦、油脂润滑三种端面摩擦条件下进行了静态压缩试验。利用电子万能材料试验机测定了载荷-位移曲线。基于各向同性弹性理论，运用能量守恒方法初步探讨了端面摩擦机理。结果表明，静态破坏应变与摩擦系数有很大关系；同一种摩擦条件下，具有粘弹特性、材料泊松比大、轴向应变大，小长径比的材料在静态压缩试验中有明显的端面摩擦效应。

关键词： 高聚物粘接炸药(PBX)、端面摩擦效应、静态压缩、能量守恒方法

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