Experimental Study on Plasma Ignited Single-base Propellant using SEM and EDS

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Abstract. To explore the reaction mechanism in the plasma-propellant interaction, plasma ignition and conventional ignition experiments are carried out on a single-base propellant. The samples after ignition are analyzed by scanning electron microscopy (SEM) and X-ray energy dispersive spectroscopy (EDS). Results show that the plasma jet brought a variety of high enthalpy flows into the propellant and deposited them on the surface of the propellant. These high enthalpy particles reacted with the propellant on the surface rapidly and produced voids and cracks different from the surface melting mode in the conventional ignition process. These voids provided microchannels for ignition and heat transmission. The area of ignition and combustion increased accordingly.

1. Introduction
The electrothermal chemical (ETC) launch technology is to discharge a plasma generator rapidly through a pulse power supply, which produces the physical and chemical reaction between plasma and propellant, generates combustion gas and forms a certain pressure to push the projectile forward. Studies show that the plasma can improve the ignition and combustion of propellant, but the mechanism of the interaction is not clear \cite{1, 2}. The surface information of the propellant after ignition is very important for the study of the plasma-propellant interaction. Many methods have been used to study and test the ignition and combustion characteristics and mechanism of propellant. Robert A. Fifer presented emission spectra from a confined PE plasma in four spectral regions \cite{3}. Jorce Newberry analyzed the surface characterization of propellant exposed to plasma by using Fourier-transform infrared microscopy \cite{4}. Michael A. Schroeder had examined the JA2 propellant samples exposed to plasma radiation by scanning electron microscope \cite{5}. Hang Yuhua established a plasma-propellant interaction (PPI) model to evaluate the ablation characteristics of different propellants \cite{6}. Jin Yong established a 3-D transient radiation model and executed plasma jet air firing experiment to discuss and analyze the mechanism of plasma from the consideration of theory and experiment. High speed camera was used to investigate the main energy transfer ways of the ablation-controlled arc (ACA) plasma diffusion process of plasma jet \cite{7}.

In this paper, conventional ignition and plasma ignition experiments are carried out. In the plasma ignition experiment, a PFN circuit was used to discharge the exploding wire, which resulted a dense (10\textsuperscript{23} - 10\textsuperscript{26} m\textsuperscript{-3}) (10000-30000 K) ionized plasma, whose composition is derived...
from the wire and sometimes from decomposed capillary material; this plasma sprays into the propellant and ignites the propellant. The morphology analyses of samples surface are executed by a scanning electron microscope (SEM) and element analyses of samples surface are performed by a X-ray energy dispersive spectroscopy (EDS). Then the analysis results of two ignition modes are compared, hoping to further understand the mechanism of plasma effect on single-base propellant ignition.

2. Experiments
2.1. Formula of propellant and instruments
A single-base propellant was chosen for ignition experiment. Shape is 11/7 and formula is: NC (94%-96%), nitrification degree 204-207.5ml/g; total volatile matter < 4.5%; external volatile matter 1.0%-1.8%; internal volatile matter > 0.9%; diphenylamine 1.0%-2.0%. X-ray energy dispersive spectroscopy (EDS) used, NORAN-VANTAGE model, was produced by Thermo NORAN in USA. Scanning electron microscopy (SEM) used was a model JSM-5610LV instrument, produced by Hitachi Electronics in Japan.

2.2. Test method
Figure 1 is the schematic diagram of experimental loop for plasma ignition.

![Figure 1. Schematic diagram of experimental loop for plasma ignition.](image)

The test procedure is as follows. Firstly, close switch 1 to charge the energy storage capacitor. Then, disconnect switch 1 and close switch 2 to discharge the capacitor. Lastly, disconnect switch
2 and close switch 3, release the residual charge in the capacitor. Charging voltage is 10kV. Value of capacitor is 37.2μF, electric energy is 1860J. The distance between the plasma jet nozzle and sample is about 10mm to 15mm. The diameter of exploding-wire is 0.1mm.

3. Results and analysis

Samples after ignition are put into vacuum bags differently and not processed until that prior to SEM examination, the samples are sputtered with gold because the samples are not conductive.

3.1. Surface morphology analysis

![Figure 2](image1.png)

Figure 2. SEM photographs of single-base propellant ignited conventionally.

![Figure 3](image2.png)

Figure 3. SEM photographs of single-base propellant ignited conventionally at different magnification.

Results are shown in the microscope photographs included as figure 2 and figure 3. Figure 2 is the SEM photographs of single-base propellant ignited conventionally. Figure 3 is four SEM
photographs of single-base propellant ignited conventionally at different magnification. As shown in figure 3, voids and cracks appear on the surface of single-base propellant, which is different from the relatively uniform surface shown in figure 2. Conventional ignition achieved ignition by accumulating the whole energy to make the propellant surface reach a certain temperature threshold which was reflected by the uniform surface of the propellant ignited conventionally.

In figure 3, there are obviously cracks with visible separation between the two sides. These are actual cracks and may be caused by the physical impact of the plasma jet. Different sizes and shapes of micropores appeared on the surface of propellant. In an unrestricted high-pressure environment, decomposition of fuel and oxidant of homogeneous propellant after interaction with plasma are out of balance, which resulted in uneven combustion and led to the appearance of these voids. The voids and cracks on the surface of propellant created by reaction with the plasma provide microchannels for the subsequent plasma jet to enter the propellant, which benefit the diffusion of plasma and heat spread. Therefore, the combustion rate increases and the whole combustion process will be shortened. On the other hand, pores and cracks generated on the surface of propellant by unrestricted plasma may lead to local combustion or incomplete combustion in an open environment. If in a high-pressure environment, such as the initial nitrogen environment of dozens of atmospheric pressure, the plasma ignition can achieve complete combustion of a single grain.

3.2. Elemental analysis

Figure 4 is the energy spectrum of single-base propellant ignited conventional. And figure 5 is the energy spectrum of single-base propellant ignited by plasma. Comparing the qualitative analysis of energy spectrum of samples ignited in two way, the number of elements in the surface layer increased in the condition of plasma ignition. The added elements were S(16), Cl(17), K(19), Ca(20), Fe(26), Cu(29). These elements are brought into the surface of the propellant with the plasma jet which produced by exploding wire and decomposed capillary.

![Figure 4. Energy spectrum of single-base propellant ignited conventional.](image)

![Figure 5. Energy spectrum of single-base propellant ignited by plasma.](image)

Corresponding quantitative analysis results of main elements (weight percent greater than 1%) are as shown in table 1. (It’s hard for EDS to analysis elements lighter than Be, such as H). It can be seen from table 1, in the condition of plasma ignition, the atomic percentages of N and O are lower than that in the conventional case. Atom percentage of N is 1.41% lower and atom percentage of O is 4.36% lower. It is considered that the chemical reaction rate of propellant ignited by plasma is faster than that of propellant ignited conventionally, which makes the content of N and O remaining on the surface of propellant decrease. Comparing these quantitative analysis results with that in reference [8], it can be concluded that single-base
Table 1. Quantitative analysis results of main elements.

| Element | Conventional Ignition | Plasma Ignition |
|---------|------------------------|-----------------|
|         | ZAF Atom(%) Wt(%)      | ZAF Atom(%) Wt(%) |
| C-K     | 2.181 40.35 33.89      | 2.419 44.87 37.36 |
| O-K     | 5.933 48.39 54.15      | 6.456 44.03 48.84 |
| N-K     | 6.970 10.34 10.12      | 8.054 8.93 8.67   |
| Al-K    | 1.970 0.60 1.14        | 1.945 0.73 1.37   |

propellant has least obviously change effect realized by plasma ignition among three kinds of propellants.

4. Conclusion
Several elements are taken into the propellant by the plasma jet. When the plasma interacted with the single-base propellant, the local physical and chemical reactions took place firstly, resulting in voids and cracks on the surface, which changed the melting mode of the propellant ignited conventionally through the energy accumulation on the surface. At the same time, these voids and cracks increased the ignition channels, and correspondingly increased the ignition and combustion area. Single-base propellant has least obviously change effect realized by the plasma ignition among three kinds of propellants.

References
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