THEORETICAL STUDY OF SHOCK WAVE IGNITION OF ALUMINUM PARTICLES

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ABSTRACT: The ignition of Al particles behind shock waves is theoretically studied with three different criteria. The first criterion is that the ignition temperature of Al particle behind shock waves is in its oxide melting point and the second is as the temperature of Al particle reaches 1350K. In this paper the third criterion is proposed that it can be ignited at the melting point of aluminum. The process of accelerating, rising of temperature and ignition of particle behind the shock waves is analyzed. The ignition delay times versus different Mach number of incident shock waves are obtained and compared with experimental results of Al particles ignition behind shock waves in oxygen with initial pressure 0.0025Mpa. Theoretical results showed that Al particles can be ignited at the temperature much lower than the melting point of Al oxide in the flow field behind shock waves. If the drag force is large enough to cause the disruption of oxide of Al particle, an Al particle can be ignited as its temperature reaches the melting point of Al and all of the Al of the particle is melted behind shock waves. The ignition delay times obtained by this criterion are best agreed with the experimental results in some conditions. If a particle is thick covered by oxide, its ignition temperature will be at the melting point of Al oxide.

1 Introduction

Al powder is widely used as additive of propellant and explosives. Thus Al particle ignition and combustion is of great practical interest and has been extensively studied[1-4]. Because Al particle is easy to be ignited to lead detonation, it is very important to study the ignition of Al particle. Al particle has a condensed and highly protective oxide film which retards further oxidation. The melting point of Al is 933K and its oxide is 2328K. In this paper ignition of Al particle in flow field behind shock waves is theoretically analyzed.

In high temperature gas with oxygen the temperature of Al particle rise due to convective heat conduction and surface chemical reaction and then is ignited. It is difficult to determine Al particle ignition temperature from experiment directly especially for small particles. It is usually considered that the ignition of particle will occur after its protective oxide film melted. This means that the temperature of oxide will be at its melting point. This is criterion 1 in this paper. But results of ignition delay time will be much longer that that of experimental ones[5].

As the temperature of Al particle rise to melting point of Al, it is made up of liquid metal confined inside a very thin layer of oxide. If the disruption of oxide film of particle occurs, the ignition of particle will be possible. Gas flow of the downstream of the shock wave may cause deformation of the particle. The stretching of the oxide film may result in particle break. This means ignition can occur at lower temperature than melting point of oxide. Veyssiere[6] assumed an ignition temperature of 1350K in Al particle ignition model. This value is significantly lower than the melting point of Al. This is criterion 2 used in this paper.

B.T.Philips and K.De Witt[7] guessed that Al fibers can be ignited near Al melting point with the help of fluid dynamic oscillation generated by resonance tube oscillation. Relative velocity between gas and Al particle can alter the bulk ignition limit by scrubbing the oxide off of the molten metal and exposing fresh surface to oxygen. In this paper it is assumed that Al particle is ignited as its temperature rise to Al melting point and all Al in particle is melted, which is criterion 3. This criterion is based on that as the temperature of particle reaches Al melting point and all the Al is melted, gas flow behind the shock wave will lead to the disruption of oxide film and ignition will occur. The ignition delay time of Al particle in the flow field behind shock wave will be obtained with these three criteria and compared with experimental ones.

2 Physical Model

It is assumed that the particles are spherical. As the Biot number $Bi=hr_p/3k_p$ 1,the particles are isothermal. The model used to analyze the ignition of Al particle is same as the model in reference [8].The energy balance equation is the following

$$\rho_p C_p V_p \frac{dT_p}{dt} = hA_s(T_g - T_p) + A_s q_r k_s - A_s \varepsilon_p \sigma (T_p^4 - T_o^4) \qquad (1)$$

The right hand side of Eq. 1 is the rate of energy transferred to the particle by convective heat transfer, the energy produced by particle surface and radiation energy to the surroundings. How to calculate them can be seen in ref. 8.

3 Results

The gas is oxygen and initial pressure is 0.0025Mpa. As the Mach number of incident shock wave changes, parameters such as velocity, density and pressure of gas flow will vary. So will the ignition delay time of particle. The analysis is processed by using Runge-Kutta method to calculated the ignition delay time of 6μm, 2μm diameter particles with different strength shock wave.

3.1 Ignition delay of Al particle with diameter 6 μm

Figure 1 shows the ignition delay time according to three criteria and experimental results[3]. Mass fraction of oxide of Al particle used in experiment is 5%. As Mach number of incident shock wave is larger than 5.86 the ignition delay time curve with criteria 3 is most agreement with experimental ones. The ignition delay time with criterion 1 is much longer than that of experiments. As Mach number is between 5.36 and 5.60, ignition delay time with criterion 2 is most approximate to experimental results. There are no experimental data as Mach number is between 5.60 and 5.86 to be compared with.

In order to consider the distribution of particle size of Al particle sample[3], the ignition delay time of Al particle with 4μm is calculated and compared with the experimental results of 6μm. From figure 2 as shock wave Mach number is larger than 5.86 the conclusion is same as above. As Mach number is between 5.36 and 5.60, experimental data are between the ignition delay time curve by criterion 1 and 2. From these results it is concluded that Al particle can be ignited as its temperature rise to Al melting point and all the Al of particle is melted.

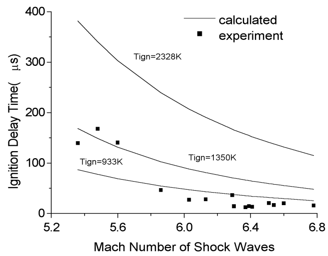

Fig.1 Ignition delay time of aluminum particles with diameter 6μm versus Mach number of shock waves

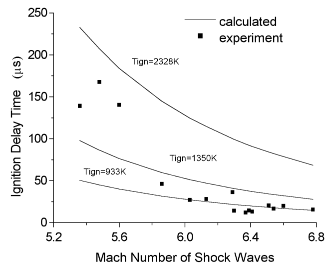

Fig.2 Ignition delay time of aluminum particles with diameter 4μm versus Mach number of shock waves

Al particle ignition is related to the drag force by the flow gas behind the shock waves. Figure 3 shows f versus Mach number of incident shock waves as particle temperature reaches Al melting point and all the Al of particle is melted. Here f is defined by $f = F / \pi r_p^2$, Where F is the drag force on the particle by flow gas. As the Mach number of shock wave is 5.86, f is 88000Pa. This means that as the temperature of Al particle rises to Al melting point and all the Al of particle is melted while f>88000Pa, the particle will be ignited. Of course this drag force is only suitable for the experimental sample. If the thickness of oxide film changes, the value f will vary to disrupt the oxide film.

Figure 4 shows particle Mach number and temperature versus time in the flow field as Mach number of incident shock waves is 5.36 and 6.37. It is assumed that the particle keeps spherical to the end of the calculation. The curve continues to the melting point of oxide. There are three stages in temperature curve. First is from initial temperature to Al melting point. In this stage particle temperature rises rapidly. In second stage temperature keeps same in Al melting point because in this stage Al is melted. In both stages chemical reaction has almost no influence on the rising of temperature. The third stage is from Al melting point to oxide melting point. In final stage, chemical reaction has obvious effect on the rising of particle temperature especially near melting point.

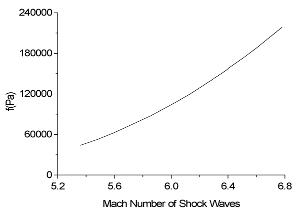

Fig.3 Calculated f as the particle temperature reaches aluminum melting point and all of aluminum in particles is melted versus Mach number of shock waves

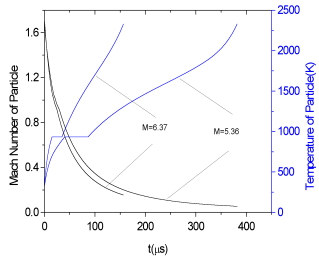

Fig.4 Calculated temperature and velocity of aluminum particle versus time

3.2 ignition delay of Al particle with diameter 2μm

Figure 5 shows the calculated results of the ignition delay time of particle with 2 μm with three criteria and experimental ones. As the Mach number is greater than 5.83, the calculated results is more appoximate to experimental ones with criterion 2 and 3. It is difficult to judge which criterion is better because of experimental data are insufficient But it can be concluded that ignition temperature is much lower than the melting point of Al oxide. As Mach number of shock waves is less than 5.42, the calculated results with criterion 1 are best agreed with experimental ones. As Mach number of shock waves is between 5.42 and 5.83, there are no experimental data to be compared with. Figure 6 shows particle Mach number and temperature versus time in the flow field as shock wave Mach number is 5.36 and 6.37.

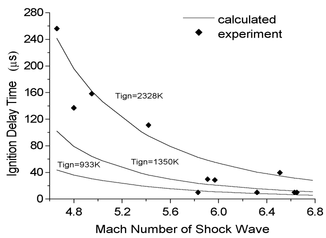

Fig.5 Ignition delay time of aluminum particles with diameter 2μm versus Mach number of shock waves

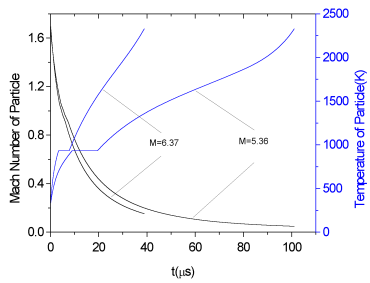

Fig.6 Calculated temperature and velocity of aluminum particle versus time

Figure 7 is the calculated results of preheated Al particle ignition delay time with criterion 1. The oxide mass fraction is 10%.Because preheated the oxide becomes thicker than usual, The results are better agreement with experimental ones by slower chemical reaction constant A_1□100. The results show that thicker oxide can not be disrupted by drag force of gas flow so that Al particle can only be ignited as its temperature reaches melting point of oxide.

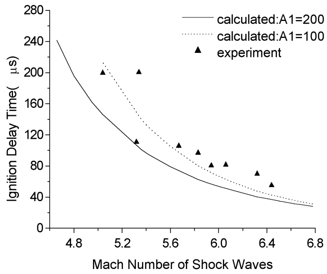

Fig.5 Ignition delay time of aluminum particles with diameter 2μm versus Mach number of shock waves

4 Conclusion

Al particle ignition delay time in the flow field behind shock waves is theoretically analyzed with three criteria. The results are compared with experimental ones. It can be concluded that Al particle ignition delay time is influenced by particle size, oxide film thickness and Mach number of incident shock waves. Al particle can be ignited at the temperature much lower than Al oxide melting point. If the drag force of gas flow on particle is strong enough to make the oxide film disrupt, Al particle can be ignited as its temperature rise to Al melting point and all the aluminum of the particle is melted. It is necessary to further study how much this drag force would be. If Al particle is preheated so that its oxide is thicker than usual, Al particle can only be ignited as its temperature reaches oxide melting point.

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