THE EFFECT OF DENSITY ON THE LIMITS AND REGULARITIES OF SPIN COMBUSTION OF TITANIUM IN NITROGEN

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A region of spin combustion in the coordinate system nitrogen-pressure (100-1800 torr)-burning sample-density (2.0-3.3 g/cm³) has been determined experimentally. The effect of density on the spin combustion characteristics (velocity, frequency, and step) has been studied at various nitrogen pressures. A transition of the spin mode of combustion to stationary with decreasing burning velocity has been observed for the first time.

Spin combustion was first observed in [1] in the burning of porous samples of hafnium, zirconium, and titanium in a nitrogen–argon mixture at a pressure of several tens of atmospheres. After spin combustion was discovered in a metal–nitrogen system, it was observed in gasless systems [2, 3], thermites [4, 5], and in a nickel–silicon mixture [6]. There are theoretical papers [7–13] whose authors confirmed the occurrence of this phenomenon and predicted a number of its peculiarities. However, one still finds a shortage of experimental data characterizing this interesting type of nonstationary combustion. One of the main parameters affecting the thermal physics of combustion and the accompanying filtration processes is the density of the solid phase through which combustion proceeds.

In the experiments we used cylindrical samples 10 mm in diameter and 15 mm in height of pressed titanium powder. The density of the samples ρ varied in the range of (2.0–3.3) ± 0.05 g/cm³. The samples were burned in a hermetic vessel in a nitrogen medium at pressure p = 100–1800 torr. The cylinders were placed in the vessel vertically and ignited from the end by an incandescent electrical coil. The process was observed and photographically recorded through transparent windows in the vessel. Measurements were made of the main parameters of the process under discussion: the burning velocity u = l/t along the sample axis, the spin combustion frequency ν = n/t (the frequency of hot spot rotation on the cylindrical surface), and the spin step s = u/ν (the distance between adjacent loops of the spin hot spot). Here t is the duration of combustion of a sample with length l, and n is the number of loops made by the spin hot spot around the sample axis within time t.

Recording the combustion process onto a moving horizontal photographic film made it possible to obtain data on the combustion mode (stationary or spin) and on all combustion characteristics. The limit of combustion (the conditions under which combustion ceases to spread) was determined from the external appearance of a sample which in this case did not burn completely. The steps of density and pressure changes were 0.1–0.3 g/cm³ and 100–200 torr, respectively.

As a result of the experiments the region of spin combustion was determined in coordinates of the nitrogen pressure and titanium-sample density [Fig. 1, region (abc)]. Outside this region, combustion is either impossible or proceeds in the stationary mode. The boundary (bc), below which combustion is impossible, constitutes the lower limit of spin combustion, and the boundary (ac), above which combustion is stationary,
forms the upper limit. It can be seen that the region of spin combustion decreases with increasing density, and at \( \rho > 2.8 \text{ g/cm}^3 \) the spin combustion mode fails to be realized.

Above the boundary (cd), combustion resembles stationary combustion (at least there are no spin hot spots), and the combustion front does not travel below this line. There are reasons to believe that the stationary mode near the boundary possesses a number of peculiarities. This process, which was first observed when titanium was burned in a mixture of nitrogen with argon or helium [14] and is outwardly distinguished by a low velocity, a vast combustion zone, and comparatively weak luminosity, has been termed "smouldering combustion." It requires a more careful investigation. Experimentally determined dependences of the velocity and frequency of spin combustion on the sample density are presented in Figs. 2 and 3. Figure 4 shows the variation of the spin step \( s \) with increasing sample density at different nitrogen pressures. The values of \( s \) were obtained using the data presented in Figs. 2 and 3. The highest values of density for each straight line in Fig. 4 correspond to the boundary conditions of the spin mode, for which with a further increase in density combustion is either impossible (lines 1-3) or becomes stationary combustion (lines 4 and 5).

As shown in [3, 5, 6, 14-17], the transition from the stationary to the spin mode involves a relative increase in heat losses from the combustion front as compared with heat release from it under the influence of such factors as changes in sample diameter, dilution of the solid and gaseous components by inert additives, and reduction of the nitrogen pressure and the initial temperature of the process. Further action in the same direction in the spin mode along with a decrease in the velocity and frequency of spin combustion also brought about an increase in the step of spin combustion, and finally conditions arose under which combustion became impossible. Thus, the spin mode preceded extinction. The effect of density on the combustion mode and characteristics proved to possess a number of interesting peculiarities, which will be dealt with below.

As can be seen from Fig. 1, a rise in sample density affects spin combustion ambiguously. At a pressure \( p > 400 \text{ torr} \) [see Fig. 1, section (ac)], an increase in \( \rho \) changes the spin mode to stationary, and at \( p < 400 \text{ torr} \) [section (bc)], sample combustion ceases. And in either case, the character of the changes in burning velocity (see Fig. 2) and the frequency of spin combustion (see Fig. 3) is the same: they both decrease with increasing \( \rho \). As can be seen from Fig. 4, this is not true of the spin combustion step. In the region of \( p \leq 400 \text{ torr} \), where a rise in density results in extinction, the spin step grows (see Fig. 4, lines 1-3), while at \( p > 400 \text{ torr} \), where with rising \( \rho \) the spin combustion becomes stationary, the spin step remains unchanged (see Fig. 4, lines 4 and 5).

Since \( s = \frac{u}{v} = \pi \frac{du}{v} \), where \( v \) is the linear velocity of hot-spot travel across a sample with diameter \( d \), the spin step, at a constant \( d \), is a characteristic of the ratio of the burning velocity along the sample axis to its transverse velocity. This means (taking into account that as \( \rho \) increases, \( u \) decreases) that at \( p < 400 \)