Effect of an Inert Filler on the Ignition Conditions of a Powder Mixture of Nickel and Aluminum

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The effect of an inert filler on the time-temperature characteristics of ignition of a nickel-aluminum powder mixture including intermetallide nucleation is examined to determine the possibilities of high-temperature synthesis of composites based on nickel aluminide.

Within the model concepts of a powder mixture of pure elements with an inert filler, we assume that
(1) inert particles or fibers are uniformly distributed in the volume of the powder mixture and divide the powder mixture into microvolumes (elementary cells) which contain a minimum amount of the powder mixture that retains the stoichiometry of the composition and is sufficient for independent initiation of intermetallide synthesis;
(2) the inert component does not take part in intermetallide synthesis;
(3) the inert component of the powder mixture does not melt during heating and ignition of the mixture.

Under these assumptions, we can use, in the calculations, the model scheme of [1] for the structure of an elementary cell of a powder mixture of pure elements. The elementary cell consists of a spherical particle of the high-melting component (nickel) surrounded by the porous low-melting component (aluminum). The size of the elementary cell is determined by the nickel particle size, because nickel melts at a higher temperature compared to aluminum. Therefore, the zones of chemical interaction in the pressed powder mixture of nickel and aluminum are localized on the surface of individual nickel particles.

The porosity of an elementary cell of the powder mixture with an inert filler is given by

\[ P_e = P/(1 - V_i), \]

where \( P \) is the porosity of the powder mixture and \( V_i \) is the volume fraction of the inert filler.

The size of an elementary cell of the powder mixture with the inert filler is defined by

\[ R_e = r_{Ni} \left( 1 - P_e \right)^{-1} \left( 1 + \frac{\mu_{Al} \rho_{Al} P_{Ni}}{\mu_{Ni} \rho_{Ni} P_{Al}} \right)^{1/3}. \]  \hspace{1cm} (1)

Here \( \mu_{Al} \) and \( \mu_{Ni} \) are the atomic weights of aluminum and nickel, \( \nu_{Al} \) and \( \nu_{Ni} \) are the stoichiometric coefficients of aluminum and nickel, \( \rho_{Al} \) and \( \rho_{Ni} \) are the densities of aluminum and nickel, and \( r_{Ni} \) is the radius of a nickel particle.

The number of elementary spherical cells per unit volume is equal to

\[ N_e = (1 - V_i)/(4/3 \pi R_e^3). \]  \hspace{1cm} (2)

The volumetric thermal capacity of the powder mixture with the inert filler is given by

\[ c_V = c_{p, Ni} \rho_{Ni} V_{Ni} + c_{p, Al} \rho_{Al} V_{Al} + c_{p, i} V_i, \]  \hspace{1cm} (3)

where \( c_{p, Ni}, c_{p, Al}, \) and \( c_{p, i} \) are the thermal capacities of nickel, aluminum, and the inert component and \( V_{Ni} \) and \( V_{Al} \) are the volume fractions of nickel and aluminum.

The heat-balance equation for the powder mixture with the inert filler in the approximation of uniform heating of the mixture by an external energy source is of the from

\[ c_V V \frac{dT}{dt} = N_e V \Phi + WS' - \alpha S(T - T_0), \]  \hspace{1cm} (4)

where \( T = T_0 \) for \( t = 0 \).
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Fig. 1. Nucleation time $t_n$ (curve 1) and the final temperature of nucleation $T_f$ (curve 2) versus the volume fraction of the inert filler $V_f$ in the starting powder mixture of nickel and aluminum (stoichiometry Ni$_2$Al).

Fig. 2. Time required for the system to attain the temperature of formation of a liquid phase $t_l$ versus the volume fraction of the inert filler for various nickel particle sizes: $r_{Ni} = 75$ (1), 60 (2), 50 (3), and 10 $\mu$m (4).

Here $V$ is the volume of the specimen, $S$ is the inner surface area of the specimen, $S'$ is the cross-sectional area through which the heat flux from the external energy source of power $W$ passes, $a$ is the coefficient of heat exchange of the specimen with the ambient medium, $t$ is time, $T$ is the temperature, $T_0$ is the initial temperature, and $\Phi$ is the heat-release rate in the elementary cell.

With increase in the fraction of the inert component in the starting powder mixture, the volumetric thermal capacity of the latter decreases, because the volumetric thermal capacity of inert components, for example, carbon, carbide, or oxide fibers, is smaller than that of nickel, aluminum, or nickel aluminides. In the present paper, carbon fibers were considered as an inert filler. In this case, it was taken into account that carbon does not form stable carbides with nickel, and aluminum carbide Al$_4$C$_3$ can be formed only at temperatures lower than 2100°C [2]. In addition, it was considered that carbon fibers having two-dimensional ordered structure are much less chemically reactive than carbon in the amorphous state. Aluminum carbide has not been detected experimentally in specimens of a Ni$_2$Al-based composite reinforced by carbon fibers and synthesized under pressure.

According to [1], in the initial period of interaction, a nucleus of the new phase forms at the interface between nickel and aluminum. When the system is heated to the final temperature of nucleation, the solid-state product Ni$_2$Al$_3$ forms at the interface between the components. After reaching the melting point of the aluminum–nickel eutectic, the product begins to dissolve intensely in the liquid phase. Equations that describe nucleation and chemical transformations in an elementary cell in the nickel–aluminum system (stoichiometry 3Ni+Al) were considered in [1].

In the calculations, we used the numerical data of [1] and the following thermal capacity and density of the inert filler (carbon fibers) [3]: $c_{p,i} = 672 \text{ J/(kg-K)}$ and $\rho_i = 1400 \text{ kg/m}^3$.

The calculations showed that with increase in the volume fraction of the inert filler, the final temperature of nucleation $T_f$ increases insignificantly (Fig. 1, curve 2). As the fraction of the inert filler increases to 70%, the temperature $T_f$ increases by only 20 K (from 780 to 800 K). In this case, the time required for complete nucleation $t_n$ decreases by a factor of two (Fig. 1, curve 1). The decrease in the time $t_n$ due to dilution of the starting powder mixture with the inert component is associated with a decrease in the volumetric thermal capacity of the system.

Figure 2 shows the time of heating of the powder system up to the formation of a liquid phase in it $t_l$ versus the volume fraction of the inert component for various particle sizes of the nickel component of the starting powder mixture. With increase in $V_f$, the time $t_l$ decreases; the smaller the nickel particle size, the greater the decrease. In this case, the decrease in the time $t_l$ with increase in $V_f$ is also associated with a decrease in the volumetric thermal capacity of the system.

In the stage of heating of a powder system of the starting elements to the temperature of formation of the liquid phase, the inert filler serves two functions. An increase in $V_f$ decreases the volumet-