**Letter**

# Pressure limits for explosive compaction of powder of aluminum-based composites

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## Abstract

This paper considers a process of explosive compaction of Al nanoparticles to create aluminum-based composites with increased physical and mechanical properties. The improvements of composite properties were obtained by the introduction of nanodiamonds and alumina nanoparticles (10 wt%. of each) into the mixture of aluminum nanopowder. As a result of theoretical consideration of the shockwave compaction for powder mixtures, we offered and discussed the conditions of explosive compaction.

The compaction process can be characterized by a set of values of the shockwave pressure which define powder compaction, deformation, and particle heating. These values are: 1. minimum shockwave pressure $P_1$ under which the compaction and the shockwave in the powder do not occur; 2. pressure $P_2$ under which there is a jet cleaning of the particle surface; 3. pressure $P_3$ that will result in a homogeneous compact with maximum density; 4. pressure $P_4$ under which particles will melt. Our research presents the result of calculations of the pressure limits for nanodiamonds, aluminum oxide, aluminum, and their mixtures.

***Keywords***: compaction, composite materials, aluminum, nanopowders, shockwave impact

## 1. Introduction

The use of materials based on aluminum composites is perspective in the aerospace industry, as well as in the automotive and construction industries. Innovative technologies demand materials with new properties surpassing properties of traditional metals and alloys. One of the methods for obtaining such materials is a nanopowder shockwave compaction. As shown Youngkook Kim et al.[1], materials produced by such the method have new properties, for example, high durability at plasticity conservation, thermal stability, wear-resisting properties, thermal and electrical conductivities, etc. The nanoparticle compaction creates new opportunities for obtaining such nanostructural alloys based on an aluminum matrix. The strengthening nonmetallic nanoparticles as nanoparticles of adamant ($Al_2O_3$) or nanodiamonds (ND) can be injected into the aluminum matrix during explosive consolidation. According to

Vorozhtsov et al.[2] and Khalid[3], such nanoparticles can improve the microstructure of the material and its mechanical characteristics.

The complexity of receiving composites from nanoparticles is that the particles need to be connected to their surface which can be extremely large ($5-50\,m^2g^{-1}$). The particle bonding depends on a condition of their surface and the surface characteristics of a material. It needs to be considered during the creation of physical models of the compaction process.

Kennedy et al.[4] showed that the powder consolidation by shock wave is characterized by a high level of deformation, and a pressure at the wave front can reach 20 GPa. The powders consolidation process is finished at about $10^{-7}$ s, during a shockwave impact. However, the physical phenomena accompanying shockwave compaction are insufficiently investigated. Therefore, there is the need for further studying of the transmitting

of pressure transient on a powder in order to obtain the necessary physically defensible ratios for assessing the main process parameters: compaction pressure, demanded time of high pressure action, etc.

The study's purpose is to determine parameters for the process of powder consolidation (pressure and time of influence) by a mathematical description of the shockwave compaction for aluminum and strengthening nanopowders.

## 2. Mathematical model of the process of powder compaction

### 2.1 Bonding time

A powder aggregation occurs on the clear surfaces of a contact. At the high rate of deformation characterizing shockwave influence, powders behave as viscous liquids. The "film folding" mechanism works in case of strong surface films which can be deformed without gaps. Under the shockwave of sufficient duration, such films can be curtailed in a ball for reduction of surface energy of a system (by Shtertser[5]). Calculations show that a compaction time for film folding and surface cleaning is hundreds of microseconds. Material characteristics depend on the rate of deformation.

By means of the description of the flow of material in a contact zone and using the Navier-Stokes equations, expressions for a speed $U_b$ of wave front of topochemical reaction (bonding wave front) were obtained in works of Kiiski. et al.[5] and Shtertser[6]:

$$U_b \sim 40 \frac{\gamma}{\eta} \qquad (1)$$

where $\eta$ is a material viscosity, $\gamma$ is a surface energy of a border between the particle material and the oxide layer.

Whereas $\gamma$ does not depend heavily on the rate of deformation $\varepsilon'$, the dependence $\eta$ on it is very high. With the growth $\varepsilon'$ by orders, $\eta$ also decreases by orders. The viscosity for various materials and rates of deformations can be found in Frost et al.[8], Kumar and Kumble[9], Godunov et al.[10].

Knowing the bonding speed and the distance between the activation centers, it is possible to estimate the bonding time $t_b$. According to Krasulin[11], the ends of dislocation represent as such activation centers:

$$t_b \sim \frac{l}{2U_b} \qquad (2)$$

where $l$ is a cell size of dislocation grid.

The value $l$ equals 1 μm in the non-deformed metals and 0.01 μm in strongly deformed metals for full bonding time during compressive stresses. When welding by explosion and shockwave compaction it is necessary to accept $l = 0.01$ μm since the material is exposed to essential deformation. The material viscosity $\eta$ strongly depends on the rate of deformation $\varepsilon'$, therefore, the bonding speed and time also depends on the rate of deformation for the material. For aluminum, we obtained $t_b \sim 2$ ms and $t_b \sim 2$ μs for deformation speed $\varepsilon' = 1$ s$^{-1}$ and $\varepsilon' = 10^4$ s$^{-1}$, respectively (Shtertser [5], [7]).

### 2.2 Pressure limits

The compaction process can be characterized by a set of values describing the shock wave which determine powder compaction, deformation type, and particle heating.

Obviously, there is a minimum shockwave pressure $P_1$, under which the compaction and the shockwave in the powder do not occur. This pressure can be obtained from the definition of shock adiabatic of the powder, according to the Carroll-Holt model [12]. The model describes compression of a porous material in the low-pressure range when particles can be regarded as incompressible, and their compaction takes place due to a change in form and material penetration into the pores. The minimum pressure is determined by the following equation:

$$P_1 = \frac{2}{3} \sigma_s \ln\left( \frac{\rho_s}{\rho_s - \rho_{pwd}} \right) \qquad (3)$$

where $\sigma_s$ is an yield strength of particle material, $\rho_s$ is a density of the solid substance, $\rho_{pwd}$ is a bulk density of particles.

For the obtaining composite, it is necessary to provide conditions for the formation of particle compounds. It is interfered by the surface layers of oxides, oxyhydroxides, adsorbed gases, etc. Cleaning from these layers (films) and connection on the cleared surface occur under shockwave influence at the microlevel.

Applying the empirical equations received by Adamec et al.[13] and Zakharenko[14] at the description of metal welding by the explosion, we received an equation for the lower pressure limit under the jet formation:

$$P_2 = 0.036 \frac{\rho_{pwd}}{\rho_s} \frac{\mathrm{HV}}{(1 - \rho_{pwd}/\rho)} \qquad (4)$$

where $\rho$ is a density behind the shockwave front, and HV is a hardness of particle material. The Equation (4) gives limits of using of the jet mechanism for the cleaning of particle surface: if the pressure in a shockwave is more than calculated by an Equation (4), the mechanism is carried out; but if it is less − the mechanism is not present. We call this pressure the second pressure limit. The Equation (4) allows to calculate pressure which necessary for the eliminating the film from the particle surface for the relative thickness $\zeta > 2.8 \cdot 10^{-6}$. The thickness $\zeta$ is determined by $\zeta = \sigma_{ox}/d$, where $\sigma_{ox}$ is an oxide film thickness, $d$ is a particle diameter.

At the same thickness of the film, the required pressure decreases with the growth of the particle size. Therefore, composite material from a powder with larger particles can be received with lower pressure than for nanodisperse powders. The mechanism of surface cleaning becomes impossible for high-disperse powders beginning with certain particle diameters because it demands nonreal high pressures.

Carroll and Holt have suggested that an adiabatic assumption found the value of $\rho$:

$$P_2 = \frac{2}{3} \sigma_s \ln\left( \frac{\rho_s}{\rho_s - \rho} \right) \qquad (5)$$

The simultaneous solution of Equations (4) and (5) allows determining the second pressure limit and the powder density behind the shockwave front corresponding to it.

A further increase of pressure under the shockwave action will result in a homogeneous compact with maximum density. The pressure limit can be obtained from the criterion of Prummer[15]:

$$D_H = 2\sqrt{\frac{1.2\mathrm{HV}}{\rho_{HEM}}} \qquad (6)$$

where $D_H$ is a detonation velocity, and $\rho_{HEM}$ is a density of the explosive. To find the shockwave pressure corresponding to the criterion, the detonation pressure can be expressed as follows: $P_H = \rho_{HEM}D_H^2/4$. According to Bakanova et al.[16], the maximal transmission factor of pressure is between 0.33 and 0.50 by pressure transfer to powders of bulk weight (in the case of a glancing detonation). Then the third pressure limit can be evaluated using the following equation:

$$P_3 \approx 0.5 \cdot \mathrm{HV} \qquad (7)$$

With a further increase in pressure, an qualitative change of the material takes place: the particle temperature reaches the melting point. If we assume uniform heating over the volume and ignore the elastic energy relative to the heat energy, we derive the following equation for evaluation of the fourth pressure limit:

$$P_4 = \frac{2\rho C_v (T_m - T_0)}{\left(\frac{\rho}{\rho_{pwd}} - 1\right)} \approx \frac{2\rho C_v (T_m - T)}{\left(\frac{\rho}{\rho_{pwd}} - 1\right)} \qquad (8)$$

where $T_m$ is a melting point, and $C_v$ is a specific heat capacity of the substance.

## 3. Result and discussion

The Figure 1 shows the bonding wave speed calculated for aluminum at different rates of deformation. The bonding speed increases exponentially with increasing the rate of deformation.

Determining the pressure limit as an additive value for a powder mixture, we can make an evaluation of these values for two types of powder mixtures: Al + 10 wt% $Al_2O_3$ and Al + 10 wt% ND. The Table 1 shows the data used in calculations.

The calculations of pressure limits for nanodiamonds, aluminum oxide, aluminum, and their mixtures are given in Table 2.

As diamond particles are very hard, the pressure limit $P_3$ is very high for a homogeneous compact with maximum density containing only diamond particles (the hardness of nanodiamonds reaches 100 GPa, according to Kennedy et al.[4]). The low-pressure limits are necessary for pure aluminum because it has the lowest hardness and melting point with the highest ductility.

Adding harder and refractory components to aluminum powder increases the pressure limits (Figure 2). As show calculations, the first three limits on pressure for aluminum and for the aluminum mixture with aluminum
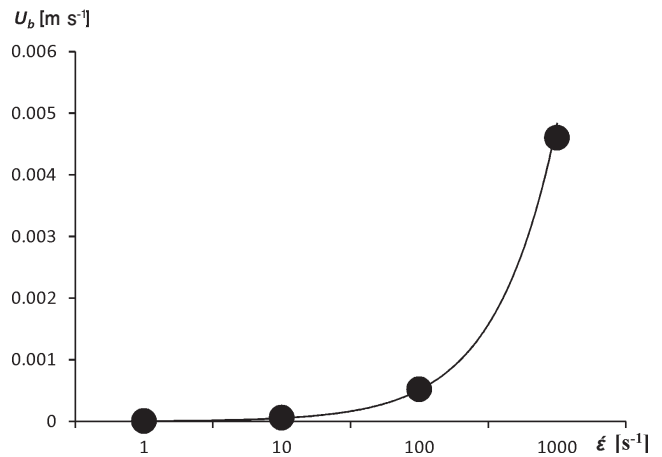


Figure 1    Bonding wave speed at aluminum powder consolidation depending on the rate of deformation.

Table 1    The materials used in calculations (G.V.Samsonov[17], Ya. B. Fridman[18], T. Mashimo[19]).

| Material | HV [GPa] | $\rho_s$ [kg m$^{-3}$] | $\sigma_s$/HV | $T_m$ [K] | $C_v$, [J (kg K)$^{-1}$] |
|---|---|---|---|---|---|
| Al$_2$O$_3$ | 15 | 3.95 | 0.35 | 2345 | 1105 |
| Al | 0.245 | 2.7 | 0.68 | 933 | 920 |
| n-diamonds | 100 | 3.5 | 0.15 | 4273 | 502 |

Table 2    Calculated pressure limits for powders of aluminum oxide, aluminum, nanodiamonds and their mixtures.

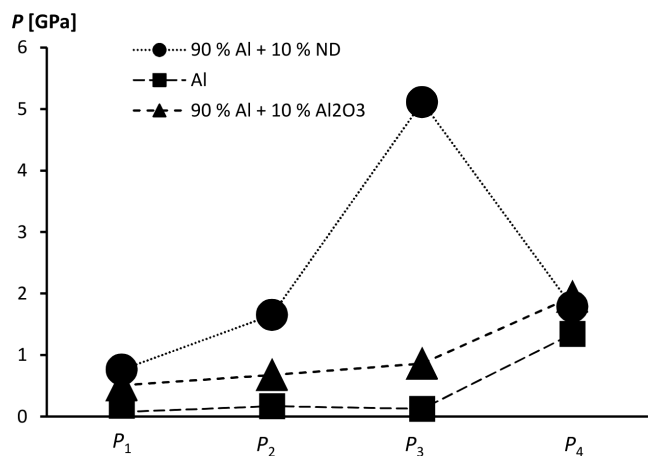| Pressure limits [GPa] | $P_1$ | $P_2$ | $P_3$ | $P_4$ |
|---|---|---|---|---|
| Al$_2$O$_3$ | 4.42 | 5.25 | 7.50 | 7.40 |
| Al | 0.0721 | 0.167 | 0.123 | 1.34 |
| ND | 6.93 | 15.0 | 50.0 | 5.75 |
| Powder mix1: Al+10 % Al$_2$O$_3$ | 0.515 | 0.675 | 0.860 | 1.94 |
| Powder mix2: Al+10 % ND | 0.76 | 1.64 | 5.11 | 1.78 |



Figure 2    Pressure limits in the process of powder compaction. Lines connect calculated dots.

oxide have about one order of size. This means that if the compaction pressure is 0.14−0.16 GPa for aluminum, a compact of the mixture of aluminum and aluminum oxide with the maximum density can be obtained at a pressure of 0.7−0.8 GPa. The higher pressures for these powders may result in undesired effects, such as particle melting (it can cause inhomogeneities and cavities in the compact

volume).

Compaction of powders containing diamond particles is complicated by the desired pressure $P_3$ which provides maximum density and homogeneity of the compact. For the example considered (a mixture of Al 90% and n-diamond 10%), this pressure is $P_3 = 5.11$ GPa. It is significantly higher than pressure $P_4 = 1.78$ GPa, at which the particles melt. Therefore, during the compaction process the pressure must be between $P_2$ (1.64 GPa) and $P_4$ (1.78 GPa). In this pressure range, there is the particle bonding but there is no material melting. If the pressure is higher than $P_4$, we can receive a relatively unconsolidated and inhomogeneous compact with melt inclusions, cavities, and, perhaps, a cavity inside the compacted cylinder due to Mach disk formation, instead of a compact with the desired maximum density.

## 4. Conclusions

On the basis of the mathematical description of shockwave compaction of metal powders, equations for the pressure limits characterizing process features were obtained: minimum shockwave pressure under which the compaction and the shockwave in the powder do not occur; pressure under which there is the jet cleaning of the particle surface; pressure that will result in a homogeneous compact with maximum density; and pressure under which particles will melt. The equation for the bonding time of particles at shockwave influence is also given. The proposed model considers the physical and chemical properties of particles: hardness, yield point, viscosity, melting point, etc.

Model calculations for powders of aluminum, adamant, nanodiamond, including, for powder mixture of such materials are carried out.

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