THE EFFECT OF SHOCK DURATION ON THE DYNAMIC CONSOLIDATION OF POWDERS

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A recently advanced model for the shock consolidation of powders predicts, for a powder of given dispersion, the regimes of shock pressure and shock duration expected to yield fully densified compacts of near optimum strength. The model is evaluated in terms of UTS measurements in compacts of rapidly solidified powders of AISI 3100 alloy, shocked to initial shock pressures between 3.6 and 17.9 GPa and to shock durations between 0.23 and 2.1 μs. We find that in powders of dispersion ≤ 1, shock durations > 1 μs are required at 10 GPa to properly solidify the melt.

1. INTRODUCTION

The consolidation of powders into well-bonded compacts involves the densification of the powder to the density of the bulk and the bonding to the particles. Dynamic Consolidation is a technique for consolidating powder materials with shock waves. During the passage of the first shock wave of amplitude P, the powder experiences a large and irreversible volume change. The shock energy E = P/ρ = m/2, where U is the specific volume and m is the powder dispersion, is deposited in the powder, preferentially near interparticle boundaries. The localization of the energy deposition produces melting at these boundaries, followed by the quenching of the melt through heat conduction into the interior of the particles. Thus the technique appears ideal for consolidating powder materials with metastable structures (e.g., rapidly solidified powders (RSP)), that cannot be sintered by conventional methods without changing their structure.

In a recent paper [1] we presented a theory for the shock-wave consolidation of powders. The theory predicts the regimes of shock pressure and shock duration which are favorable for obtaining compacts with good mechanical properties. The theory is based on the concept of hardness (HDP) and ultimate tensile strength (UTS) measurements in shock-consolidated samples from RSP of AISI 9120 alloy, described in a companion paper, [2]. These experiments were performed at a constant shock duration of approximately 1 μs varying the shock pressure.

In the present paper we discuss and evaluate our theory. In terms of UTS measurements in samples consolidated by an initial shock pressure of 10 GPa and varying shock duration.

2. DESCRIPTION OF THE MODEL

The dynamic consolidation of powders involves several distinct processes, which can be characterized by time constants τ. These processes are: 1) the densification of the powder and eventual melting of the particle surfaces (time constant τ1), 2) the solidification of the interparticle melt by heat conduction into the particle interiors (time constant τ2), 3) the thermal relaxation of a compact with hot boundaries and cooler interiors to an homogeneous temperature T (time constant τ3), and 4) the thermal relaxation of the compact from T to the ambient temperature (time constant τ4).

The densification of the powder takes place during the shock rise time, of duration τ1. Measurements of τ2 in RSP of 9120 alloy with an average diameter of 60 μm and distortion m = 1.7, shocked to a pressure of 10 GPa and shock velocity u = 2.3 mm/s, gave τ2 = 40-10 ns. [3] This indicates that, for these parameters, the width of the shock front is approximately one particle diameter. Similar conclusions follow from the micrographs of Morris [4] of compacted steel powders of 1 μm diameter, shocked to pressures of 3-5 GPa. The distinct etching of the melted particle boundaries shows that the boundaries are radiated concentrically with respect to the shock wave propagation direction. This clear asymmetry can only result if the width of the shock front is approximately one particle diameter, or less.

Micrographs of compacts, sectioned and etched so as to reveal the original particle boundaries [2,4-6], show extensive plastic deformation of the original particles. Thus, part of the energy is dissipated within the particles. Numerical estimates of the energy stored in the elastic strain field of the dislocations [6] show that it is small compared to the bulk energy E. No reliable estimate has been made of the work dissipated by the viscous motion of dislocations in the interior of the particles. Based on the observations that plastic flow is significantly larger near the boundaries of the particles.
than in their interiors, and in the detection of material between particles that reached the molten zone during the shock consolidation [5-7], the models that have been proposed to explain the consolidation of powders [8,9,10] assume that the shock energy is distributed uniformly throughout the particle interiors. Provided the heat fluxes during T_g from the molten layer to the cooler particles is a negligible fraction of E_p, immediately behind the shock front the particles will be surrounded by a molten layer of thickness \( h = \alpha_d \), where \( \alpha_d \) is the mass flux melted [1]. In the presence of superheating, \[ L = E_p / \left( \alpha_d - T_p - T_s \right) + h^2 \] (1)
where \( E_p \) is the average value of the specific heat between the initial powder temperature, \( T_p \), and its melting temperature, \( T_m \), and \( h \) is the latent heat of melting.

The conditions for which equation (1) are applicable require further discussion. During this, the heat flux advances into the particle interiors a distance of order \( 4(\alpha_d) T_p / \alpha_d \), where \( B \) is the thermal diffusivity. Thus, the assumption that initially \( E_p \) is stored nearly in the melted material is valid provided \( 4(\alpha_d) T_p / \alpha_d \ll \alpha_d \). For RSP of 9130 alloy of 60 \( \mu \)m diameter, and with \( \alpha_d \approx 40 \text{ ms}^{-1} \), equation (1) is applicable for \( L > 0.30 \), since the shock-consolidation of these powders into compacts with strengths approaching that of the wrought alloy requires \( L \) values in excess of 0.2. Equation (1) can be used to study the conditions for shock-consolidation into strong transverse compacts.

The molten layer surrounding the particles solidifies by heat conduction into the interior of the particles. The evaluation of the solidification time requires numerical computations which are then applicable to a particular powder material and particle size. For \( h < 0 \), the solidification problem can be approximated by that of a molten slab of thickness \( h/2 \) in contact with a semi-infinite solid at the initial temperature \( T_0 \). For a fixed solid-liquid interface and assuming no superheated melts, the solidification time is \( \tau_s = A (Ld)^2 \) (2)

where \( A \) contains parameters describing the thermal properties of the particle material [11]. Following the solidification of the melt, the temperature of the compact is highly nonuniform. The relaxation time \( \tau_s \) for reaching a homogeneous temperature \( T_s \) is of order 4(\alpha_d) T_s

[1] Finally, the cooling of the compact from \( T_s \) to the ambient temperature \( T_0 \) requires a minimum time \( \tau_c \) of order \( \tau_d / \alpha_d \), where \( \alpha_d \) is the smallest dimension of the compact. In general \[ \tau_d < d, \]
so that \( \tau_c >> \tau_d \).

The question now arises, knowing the time constants \( \tau_s \) and \( \tau_c \), that characterize the thermal behavior of the powder under shock compression, what are the values of shock pressures \( P_0 \) and shock duration \( t_0 \) that result in compacts of optimum strength? General criteria, based on the amount of melted material needed to bond the powder particles, and on the time in which the melt must solidify, are now introduced.

2.1 Minimum Shock Energy

In the present model the melted mass fraction is proportional to the shock energy. Properties of shock compacted RSP of 9130 alloy support this qualitatively. With increasing values of shock energy, it is observed that: (a) the original particle boundaries, as revealed by etching the recovered compacts, disappear progressively; (b) the fracture mode, as soon by TEM, changes from intergranular to transgranular and becomes more brittle; and (c) the Young's modulus of the compacts increases monotonously. However, the ultimate tensile strength (UTS) of the compacts has a more complicated behavior. Figure 1 in Ref [8] shows that for \( E_p < E_p \approx 180 \text{kJ/kg} \), the compacts have negligible strength. The ultimate tensile strength increases rapidly, reaching maximum at \( E_p \approx 500 \text{kJ/kg} \). Several mechanisms have been advanced [12] to explain the shock-energy threshold for nonzero strength, because this threshold has not been sufficiently studied as a function of material and powder parameters; the criterion for strong compacts must be presently derived empirically. We adopt as a sufficient condition for strong compacts the expression \[ 0.5 \sigma_{UTS} \text{ dyn/cm}^2 \]

where \( \sigma_{UTS} \) is defined as the measured micro-hardness of the compact and the powder compacted at 150 \text{kJ/kg} and hardened in wrought 9130 alloy shocked to 15 \text{kJ/kg} [8] for a powder of 60-\( \mu \text{m} \) diameter particles, our strength criterion requires \( E_p \approx 3.2 \times 10^5 \text{ J/kg} \) (3)

For this shock energy the model predicts \( L = 0.22 \).

2.2 Minimum Shock Duration

The successful consolidation of the powder requires that the melted region solidify while the sample is still in the shocked state. Otherwise the sample at high density and high temperature will cool at high rates, instantly at low thermal gradients. This requires \( \tau_s > \tau_c \). From equations (1) and (2) we follow that the minimum shock duration is \[ \tau = \tau_s \approx \tau_c \]

where \( E_p \) contains thermal parameters of the powder. Equation (4) is only valid in the limit \( L < 0.3 \). At \( L = 0 \), and thus \( \tau_s > \tau_c \), the minimum value of \( \tau_s \) must increase nearly as \( L \approx 0 \) increases. As the velocity \( U_p \) is increased to 3.5 times transverse, it is clear that strong compacts of high shock energy and low thermal conductivity may be obtained.
dation technique loses its advantages over conventional sintering. Keeping the shocked compact at temperatures approaching T_f for a time τ_f may cause recovery and grain coarsening, which should result in a decrease of the DS and DM. This decrease is indeed observed. [8]

The conditions of equations (3) and (4) define the regime of shock energy and shock duration expected to yield strong compacts. These conditions are shown in Fig. 1. In the figure the shock energy has been normalized by the thermal content of the compact, E_p (Eq. 1), and the shock duration has been normalized by the thermal relaxation time, τ_e.

The points in Fig. 1 correspond to shock consolidation tests in RSP of 9310 alloy. The circles are experiments at constant shock duration and varying shock energy. These were reported in recent publications. [12] The squares are experiments at constant shock energy and varying shock duration. These will be described next.

3. EXPERIMENTS

Rapidly solidified A151 9310 alloy powder with an average particle diameter of 60 μm was statically compacted into a cylindrical shape of 35 mm diameter and 10.2 mm thickness. This sample, with a density ρ = 1.47 g/cm³, was then dynamically compacted by a stainless steel flyer, 40 mm in diameter and 5.2 cm in thickness, accelerated by propellants in an evacuated gun to an impact velocity of 1.16 mm/μs. Figure 2 shows the position-time relation for the initial shock and release waves in the flyer and powder. In plotting this figure we assumed that the shock impedances of the flyer and the compacted powder are the same.

Figure 1: Map of Dynamic Consolidation for rapidly solidified powder of A151 9310 alloy.

Figure 2: Time-position histogram followed during the initial shock compaction of the specimen in Fig. 1.

Because the densification of the powder occurs at the front of the first shock wave, following shocks should have little relevance in the consolidation. As can be seen in Fig. 2, the powder at the impact surface exhibits the initial shock pressure for a time interval of 2.1 μs. Points below the impact surface are subjected to a shorter initial shock pressure. The release waves catch up with the initial shock at a depth of approximately 4 mm. Figure 2(a) shows one half of the cross section of the recovered compact. The arrows indicate the propagation direction of the initial shock. The long crack parallel to the shock front is associated with the trace of the surface where the release wave caught up with the initial shock. The small vertical cracks are associated with the deformation of the compact following the shock consolidation. Three slices, parallel to
the shock front, were cut from the compact by spark erosion. From each of these, three dog-bone-shaped tensile specimens were cut, also by spark erosion, as shown in Fig. 3 (b). The small rectangles in Fig. 3 (a) show the position, within the compact, of the cross-section of the tensile specimen. For each specimen, the duration \( t_0 \) of the initial shock was calculated as \( t_0 = 2.1 \sqrt{y_j} \) (s), where \( y \) and \( y_j \) are the distances from the specimen to the impact surface and from the cross to the impact surface, respectively.

The squares in Fig. 4 show the UTS of the specimens as a function of \( t_d \). The circle is the result of tensile tests in compacts of the same powder, consolidated at the same value of shock pressure, but in a 20 kw bomb. [2] The present results are also shown in Fig. 3, where the half-filled square denotes that the specimen shocked for the shortest \( t_d \) failed our strong-compaction definition. The results of tests at constant \( t_d \) and varying \( t_s \) (see Fig. 1 in Ref. [2]) and the present results for constant \( t_s \) and varying \( t_d \) (Fig. 4) support the model, as summarized in Fig. 2. Furthermore, they indicate that the optimum strength is obtained towards the center of the shaded area in the shock-consolidation map.

REFERENCES


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Figure 5: (a) Cross section of a shock consolidated specimen. (b) Slices of specimen for the preparation of tensile specimen.

Figure 6: UTS versus shock duration for RSP of AISI 851 alloy consolidated at a shock pressure of 9,5 GPa and shock energy of 4.04 x 10^4 J/kg.