The shock-densification behavior of three distinct Ni+Al powder mixtures

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The shock-densification response of equivolumetric mixtures of Ni+Al powders of varying particle size and morphology has been determined through instrumented parallel-plate impact experiments. The results reveal a variation in the densification response, with crush strengths (stress at full density) ranging from 0.5 to nearly 6 GPa. A modified Fischmeister–Artz contact model was proposed to predict the crush strength of configurationally varying Ni+Al powder mixtures. © *2008 American Institute of Physics*. [DOI: 10.1063/1.2896653]

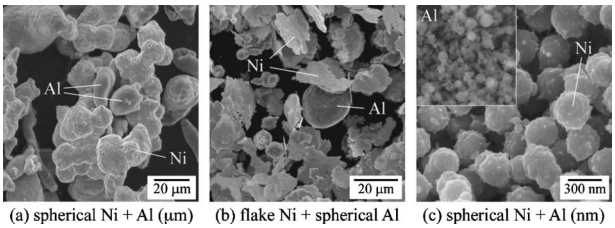
The formation of near-net density solids from metal powders is usually thought to occur more easily at high strain rates. The stresses involved in dynamic compaction processes greatly exceed the yield strengths of the starting components and interfacial barriers, rapidly eliminating the interparticle voids. Recent work has shown, however, that the stress required to achieve full density is not invariant and depends upon parameters such as particle size.[1]

The consolidation behavior of powders is characterized by the "crush-up" process, which describes the pressure-volume states linking the initial, distended state to the solid Hugoniot. Several approaches have been developed to predict the crush-up response, including the P-α (Ref. 2) and P-λ (Refs. 3 and 4) models. Unfortunately, these models largely ignore the specifics of powder configuration and are therefore limited in application. Powder mixtures possess perhaps the widest potential for variability of any material, with limitless combinations of phases and constituent properties, particle sizes and shapes, and orientation, and nearest neighbor distributions. Proper prediction of the behavior of these materials requires models that consider these variables.

In the current work, the influence of configuration on crush-up response was investigated for three distinct equivolumetric Ni+Al powder mixtures (Fig. 1). The mixtures consisted of (a) micron-scale spherical Ni+Al, 60% theoretical maximum density (TMD), (b) micron-scale flake Ni +spherical Al, 45% TMD, and (c) nanoscale spherical Ni +Al, 40% TMD. The micron-scale powders were obtained from a commercial vendor specified as −325 mesh. The nanoscale Al was supplied by Technanogy and was approximately 50 nm. The nanoscale Ni was produced through a reduction-in-solution chemical precipitation process,[5] yielding particles 50–300 nm in diameter. The powders were mixed with a v-blender for 24 h, and then statically pressed into discs approximately 50.8 mm in diameter and 1.5 to 3.75 mm in thickness. This large aspect ratio was necessary to avoid early-time radial effects and maintain a one-dimensional shock-propagation event during the diagnostic lifetime. The pressed powder was confined within a specimen assembly, as shown schematically in Fig. 2. Polyvinylidene fluoride (PVDF) stress gauges, sandwiched between 25 μm thick layers of Teflon insulation and coated with 100 nm of Al, were located at the driver/specimen and specimen/backer interfaces to provide a measure of the shock profile and shock-transit time through the specimen. Shock compression was generated through impact of the driver by an aluminum-supported flyer plate, launched by an 80 mm bore, single-stage helium-driven compressed gas gun in the range of 50–1100 m/s. From the gauge response, the input stress P and shock velocity U_s were directly obtained. Assuming first order effects and applying the Rankine–Hugoniot jump conditions permitted calculation of the P-V state of the material at high pressure.

The details of the shock-compression experiments performed on the three mixtures up to 6 GPa are listed in Table I, where the mixtures are referred to by their designations in the preceding text. For clarity, only those experiments that reveal details of the crush-up process are listed. The input stress and shock velocity are measured parameters (using gauges) and particle velocity and relative volume are calculated values. A plot of the pressure-volume data is also shown in Fig. 3. Included are the initial states of the starting powders, which range from a relative volume of 1.67 to 2.5. In the case of the micron-scale spherical Ni+Al mixture, full density was achieved at approximately 0.5 GPa. This is in good agreement with a preliminary Fischmeister–Artz calculation of the crush strength (0.4 GPa), where the strength of the mixture was assumed to be dominated by the yield strength of nickel (~135 MPa). For the flake Ni+spherical Al mixture, the crush strength appears to have increased to ~2 GPa. Results for the nanoscale Ni+Al powder mixture indicate a further increase in the crush strength over the micron-scale mixtures. The reduction in particle size from ~25 μm to 50–300 nm results in a crush strength of nearly 6 GPa.

Clearly, these results indicate that the shock-densification behavior of a powder mixture is quite sensitive to parameters such as particle size and morphology. While the initial densities of the three mixtures also vary, they are not thought to dominate the densification process, nor be



(a) spherical Ni + Al (μm) (b) flake Ni + spherical Al (c) spherical Ni + Al (nm)

FIG. 1. Scanning electron micrographs of the three starting (loose) Ni+Al powder mixtures.

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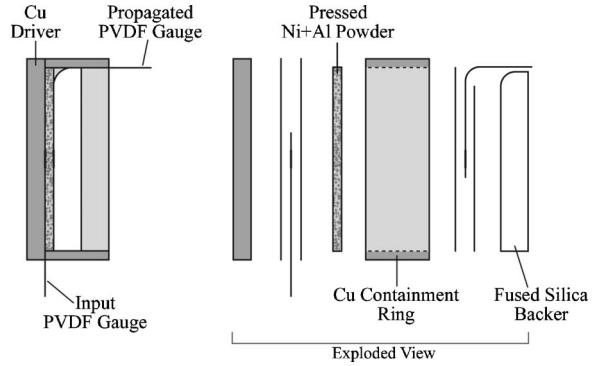

FIG. 2. Configuration of the parallel-plate impact experiment for powder mixtures. The input and propagated stress are recorded by two PVDF gauges, which also give the shock-transit time through the specimen.

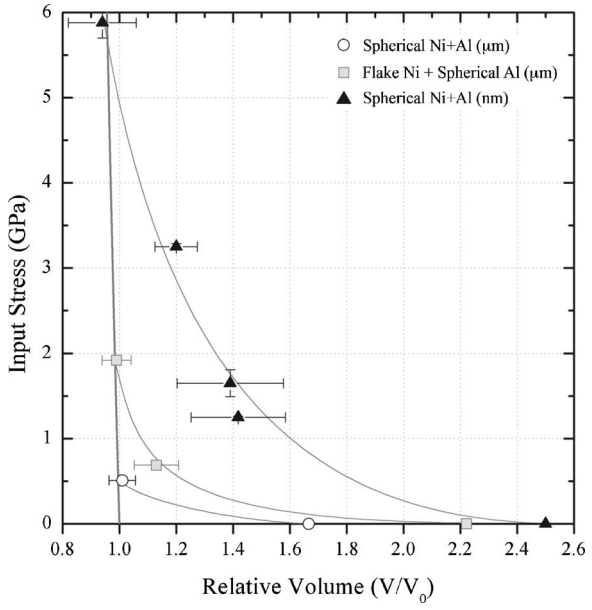

FIG. 3. Pressure-volume data obtained up to the Hugoniot of the dense solid for three distinct Ni+Al powder mixtures. The initial states are also noted along the abscissa. The crush strength shows a strong dependence upon the powder configuration, ranging from 0.5 to nearly 6 GPa.

responsible for the wide range in crush strengths. Instead, the large variations in densification response are believed to reflect the complex interplay between particle mass flow and surface resistance to such flow. The large particle sizes and minimized particle surface areas in the micron-scale spherical Ni+Al mixture results in elimination of the void volume through preferential deformation of the softer Al phase, as revealed through scanning electron microscopy (SEM) of postshocked specimens.[6] As for the flake mixture, SEM of an as-pressed flake mixture reveals that the flakes are aligned normal to the direction of shock propagation.[7] As such, most of the void volume is localized between the flakes and cannot be eliminated solely by the deformation of Al. Rather, densification must result from plastic flow of the Ni particles, which is encumbered by the very large surface energies of the flake particles. Similarly for the nanoscale mixture, the densification process is greatly hindered by the tremendous amount of particle surface area, which is active in both soft and hard phases.

An attempt was made to correlate the differences in mixture configuration with the observed crush strengths. First, the variations in particle size and morphology were generalized according to their influence on the amount of particle surface area per unit volume of mixture SA_v. Average particle sizes of 25 μm, 100 nm, and 50 nm were assumed for the micron-scale particles, nanoscale Ni, and nanoscale Al, respectively. The flake particle thickness was assumed to be 300 nm. From these, a plot was constructed detailing the change in SA_v with initial density (Fig. 4), where the arrows indicate the mixtures considered in this work. As shown, the initial density does not significantly influence SA_v within the regime considered and thus is not thought to be the principal cause of the disparate mixture strengths. The slope n of linear fits (note the log scale) for each of the three mixtures were then used to modify the Fischmeister–Artz contact-point model[8] to include the effects of mixture configuration, where the crush strength can be expressed as

$$P_y = 2.97\rho^2\left(\frac{\rho-\rho_0}{1-\rho_0}\right)\sigma_y\left(\frac{n}{n_0}\right)^{0.473},$$

where ρ and ρ_0 are the final and initial relative densities, σ_y is the yield strength of the mixture, and the reference slope $n_0 = 1200\ \mathrm{cm}^{-1}$ is taken from the spherical −325 mesh mixture. This equation is plotted in Fig. 5 along with the corresponding experimental data. The bold curve shown gives the crush strength of a wide range of configurationally varying equivolumetric mixtures of Ni+Al. Alternative mixture stoichiometries may influence the net mixture yield strength, e.g., decreasing strength with increasing Al content. Consequently, the crush strength, as indicated by the dashed and dotted curves, is altered.

In summary, the consolidation response of three configurations of Ni+Al powder mixtures has been investigated through parallel-plate impact experiments performed up to 6 GPa. Results reveal a strong correlation between mixture

TABLE I. Results of the parallel-plate impact experiments performed on three distinct Ni+Al powder mixtures. The mixture number corresponds to their definition in the main text. The input pressures were selected based upon the method described by Xu and Thadhani (Ref. 9).

Mixture	Initial density (%TMD)	Impact velocity (mm/μs)	Input stress (GPa)	Shock velocity (mm/μs)	Particle velocity (mm/μs)	Relative volume
a	60.7	0.250	0.51 ± 0.02	0.61 ± 0.01	0.24 ± 0.01	1.01 ± 0.05
b	44.5	0.430	0.69 ± 0.03	0.74 ± 0.01	0.36 ± 0.02	1.13 ± 0.08
b	44.5	0.669	1.92 ± 0.02	1.16 ± 0.02	0.64 ± 0.02	0.99 ± 0.05
c	38.6	0.455	1.25 ± 0.01	1.11 ± 0.06	0.50 ± 0.04	1.42 ± 0.17
c	38.0	0.684	1.65 ± 0.16	1.26 ± 0.03	0.59 ± 0.07	1.39 ± 0.18
c	38.4	0.925	3.25 ± 0.04	1.65 ± 0.03	0.89 ± 0.03	1.20 ± 0.07
c	40.3	0.953	5.88 ± 0.18	2.01 ± 0.04	1.25 ± 0.07	0.94 ± 0.12

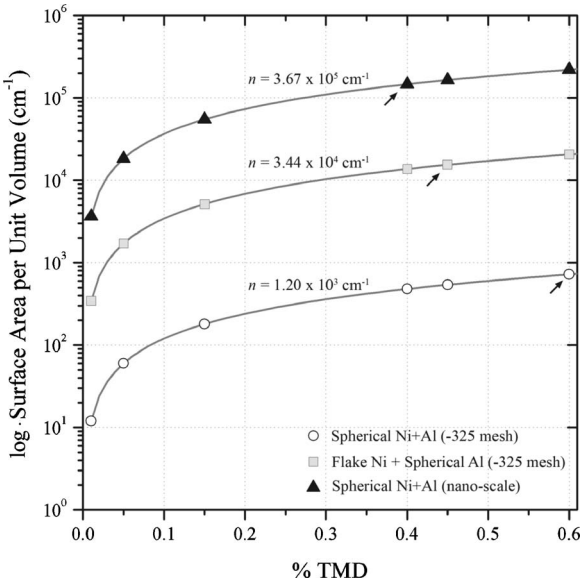

FIG. 4. Estimates of the surface-area per unit volume for the three Ni+Al mixtures as a function of initial density. The arrows indicate the mixtures that were considered in this work.

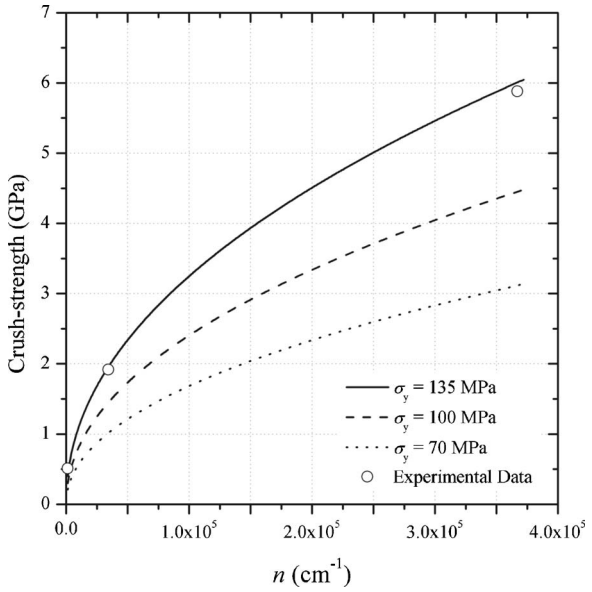

FIG. 5. Plot of crush strength as a function of mixture configuration parameter for the equivolumetric Ni+Al system (bold). The dashed and dotted curves indicate the effect of mixture yield strength, which might be affected by mixture stoichiometry.

parameters (e.g., particle size and morphology) and the resulting crush strength. The crush strength was shown to range from 0.5 GPa for a micronscale spherical Ni+Al mixture to nearly 6 GPa for a nanoscale spherical Ni+Al mixture. This wide range in consolidation behavior indicates the importance of incorporating such configurational parameters in dynamic densification models. A mixture configuration parameter, based upon the amount of particle surface area per unit volume, was introduced to modify the Fischmeister–Artz contact-point model to include the effects of particle size and morphology, yielding a generalized equation for the crush strength of an equivolumetric Ni+Al mixture.

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[1]C. Dai, D. E. Eakins, N. N. Thadhani, and J. P. Liu, Appl. Phys. Lett. **90**, 071911 (2007).
[2]M. M. Carroll and A. C. Holt, J. Appl. Phys. **43**, 759 (1972).
[3]D. E. Grady, N. A. Winfree, G. I. Kerley, L. T. Wilson, and L. D. Kuhns, J. Phys. IV **10**, 15 (2000).
[4]D. E. Grady, *Analytic Solutions and Constitutive Relations for Shock Propagation in Porous Media* (American Institute of Physics, New York, 2003), pp. 205–208.
[5]D. V. Goia and E. Matijevic, New J. Chem. **22**, 1203 (1998).
[6]D. E. Eakins and N. N. Thadhani, Investigation of Shock-Induced Reaction in a Ni+Al Powder Mixture, in *American Physical Society, 14th APS Topical Conference on Shock Compression of Condensed Matter* (American Institute of Physics, Baltimore, MD, 2005), pp. 1153–1156.
[7]D. E. Eakins and N. N. Thadhani, J. Appl. Phys. **100**, 113521 (2006).
[8]H. F. Fischmeister and E. Arzt, Powder Metall. **26**, 82 (1983).
[9]X. Xu and N. N. Thadhani, J. Appl. Phys. **96**, 2000 (2004).