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THE INFLUENCE OF PARTICLE MORPHOLOGY ON THE DYNAMIC DENSIFICATION OF METAL POWDERS

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Abstract. Powders are well known for their dispersive properties, which derive from the many dissipative processes that occur during densification. While numerous studies have been devoted to understand these processes over a wide range of initial densities, the influence of particle morphology has been for the large part overlooked. In this paper, we discuss a new research campaign at the Institute of Shock Physics, to systematically investigate the role of starting configuration on the dynamic densification of metal powders. Multi-target gun loading experiments have been performed on both stainless steel and copper powders of equiaxed- and fiber-shaped morphology. Frequency-shifted PDV was employed to measure the structure and velocity of the dynamic densification wave, to yield the crush strength of the various powders. We find that while the crush strength for the stainless steel powders is reasonably described by a modified Wu-Jing model, this model underpredicts the densification stress for the copper powder.

Keywords: Powders, densification, morphology

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INTRODUCTION

The dynamic loading of a granular material activates a number of microscale processes responsible for the dissipation of the compression wave. The extent and distance over which these waves can be attenuated are important properties for shock mitigation, and rely upon understanding the behavior of powders under strong and weak loading. While earlier studies have shown the high stress behavior of porous materials to be insensitive to powder configuration [1], prior work on metal powder mixtures demonstrated that both powder morphology and particle size play a strong role in densification at low stresses [2, 3].

There is currently no robust model for dynamic densification that includes the effects of powder configuration. The popular models in use ($P - \alpha$, $P - \lambda$, etc.) are generally empirical, and were not intended to capture surface-level processes such as local flow, fracture, and melting. Understanding the link between these processes and powder configuration, i.e., shape, size, orientation, etc., is the key to developing

physically-based predictive models for dynamic densification.

EXPERIMENT DETAIL

The densification response of three metal powders was explored through plate-impact experiments performed using a 100 mm diameter single-stage gas gun. The experiments utilized a new target fixture (Figure 1) to allow simultaneous testing of multiple samples, and thereby, direct comparison of material response. The 120 mm diameter target fixture consisted of a 4 mm thick Al 6061-T6 driver, backed by a 30 mm thick 316L stainless steel multisample powder cell. The cell contained three 40 mm diameter bore holes on a 51.24 mm PCD, and additional holes for measurement of impact velocity, impact time, shock front tilt, and input wave structure. All surfaces were lapped and parallel to within 100 μ rad.

The metal powders considered in the current study are listed in Table 1. They consisted of an equiaxed

FIGURE 1. A partial cutaway of the multipowder target fixture designed for the dynamic crush-strength measurements.

TABLE 1. Description of tested powders.

Index	Material	Shape	Size
a	316L SS	round	-325 mesh
b	434 SS	fiber	50 μm dia. x 2-3 mm
c	Cu	round	8-11 μm dia.

(round) 316L stainless steel (Alfa Aesar #88390), a fiber-shaped 434 stainless steel (Deutsches Metallfaserwerk DIN 1.4113), and an equiaxed copper (Alfa Aesar #13990), as shown in Figure 2. The copper was substituted for a flake-shaped 316L steel powder due to complications during pressing. The equiaxed powders were sequentially loaded and pressed into the steel fixture to a target height and density of 4 mm and 55% TMD, respectively. Due to limits on the load frame, the steel fibers could only be pressed to 44% TMD.

A PMMA window was sealed into contact with the as-pressed powders. The window was constructed of a 2 mm PMMA buffer affixed to an 8 mm thick, 5° PMMA wedge. The contact surface of the PMMA wedge was diffusely polished with 5 μm diamond paste to ensure a return signal from the irregular shock front, and coated with a flash of aluminum. The wedge was necessary to reject the free surface back-reflection, which would otherwise dominate the weak return signal.

The principal diagnostic was an 8 channel multi-gen PDV system operating at 1550 nm. A single -25 dB collimating probe was used to record the im-

FIGURE 2. Scanning electron micrographs of the (a) equiaxed stainless steel, (b) fiber stainless steel, and (c) equiaxed copper powders.

pact velocity, while four bare-fiber probes measured the arrival of the shock front on the powder-side of the aluminum driver plate. The motion of the embedded Al film was simultaneously monitored for each powder using -60 dB collimating probes, and a frequency-shifted reference, to improve sensitivity to any low-amplitude precursor waves.

Prior to the experiments, the Hugoniot and crush-up curves for the three mixtures were calculated using the Wu-Jing model [4], which constructs the powder states based upon an isobaric shift from the Hugoniot of the solid. For the low stress regime, the Wu-Jing model implements the Carrol-Holt form of the $P - \alpha$ model [5]. In the present study, the $P - \alpha$ model was modified according to the method outlined in [3], in which a configuration parameter, n , was introduced to take into account the surface-area of the various powders. This parameter was used to scale the Fischmeister-Artz crush-strength, and establish new limits for the Wu-Jing crush-up regime.

RESULTS

Four symmetric plate-impact experiments were performed at impact velocities of 344.6, 397.5, 467.5, and 587.9 m/s. The impact tilt in each experiment was between 0.6 - 1.4 mrad.

An example set of frequency-shifted PDV measurements is shown in Figure 3, recorded for the experiment conducted at 344.6 m/s. The persistent signal centered near 3950 m/s (shifted velocity) arises from a combination of the partial reflection from the wedged surface, and the back-reflectance at the probe connectors. Each trace reveals a low amplitude precursor (1) followed by a sequence of densification

FIGURE 3. Representative frequency-shifted HetV traces processed using a 20 ns Hamming window for the (a) equiaxed steel, (b) fiber-shaped steel, and (c) equiaxed copper powders. Features in the wave profile include the (1) precursor, (2) powder/PMMA reshock state, and (3) Al driver reflection.

fronts (2 and 3). The leading front (2) corresponds to the reshock state at the powder/PMMA interface, while the following (3) is a second reshock originating from reflection at the Al driver plate.

The initial densified state in the powder was determined from the first reshock (2) shown in Figure 3. The reshock state lies on the principal Hugoniot of PMMA, and can thus be used to determine the transit time through the PMMA buffer, and by correction, the transit time through the powder. The resulting powder shock velocity was then impedance matched to the release states from the Al/Al impact, taking into account the effect of strength observed in the bare-fiber tilt probes, to determine the stress at the powder/Al driver interface.

The measured states for the three powders are shown in stress-volume space in Figure 4, along with the Hugoniot of the corresponding solid and surface-area modified Wu-Jing model. The measurement uncertainties were calculated using a rigorous error analysis taking into account covariance. The scatter in the data is attributed to sample consistency and

uniformity, rather than measurement precision. It is well-known that density variations are produced during powder pressing [6], such that an average density measurement does not necessarily reflect the true density through the volume probed.

A clear difference in bulk response is observed for the stainless steel powders. The equiaxed powder approaches a crush strength of nearly 2 GPa, while the fiber-shaped powder densifies around 1.5 GPa. Reasonable agreement is observed between the experiments and modified Wu-Jing model, using configuration parameters of 1500 cm^{-1} and 810 cm^{-1} for the equiaxed and fiber powders, respectively. This behavior is consistent with earlier observations of morphology dependence, as the smaller equiaxed particles contained more than double the surface area per unit volume, S_v , as the fibers.

The results for the equiaxed copper indicate the lowest crush strength of the three powders, with all of the data over 92% dense above 0.9 GPa. Using a yield strength of 100 MPa and a particle size of $11 \mu\text{m}$ to estimate a configuration parameter of 5454 cm^{-1} , the modified Wu-Jing model appears to underpredict the crush strength. This discrepancy may have its origins in the choice of yield strength, Y , which is strongly dependent upon processing and can easily range between 100–400 MPa. Alternatively, the error could be in the assumption of a spherical particle geometry when, as shown in the SEM images, the copper powder is highly irregular. These factors can more easily be elucidated in the intermediate crush regime, where their contributions are more distinct. This indicates a need to measure the yield strength and surface area of the particles, and to extend future experiments to lower stresses.

The PDV wave profiles can also reveal clues to the processes taking place at the microscale. In particular, the precursor waves give an indication of the extent and mode of early force transfer through the powder bed. The limited separation between precursor and initial densification front in the equiaxed steel powder suggests a limited particle contact network, conducive to rearrangement processes. In contrast, the copper precursor exhibits a broad separation, signifying a contiguous network of particle contacts. However, it is the precursor in the steel fibers that is particularly intriguing, as its initial reverse motion may be linked to extensive transverse motion arising from the anisotropy of the particle bed. These processes also influence the rise-time of the initial

FIGURE 4. Stress-volume results for the (a) equiaxed stainless, (b) fiber-shaped stainless, and (c) equiaxed copper powders, along with the surface-area modified models of densification response. The copper model appears to underpredict the crush-strength, although reasonable agreement can be found by increasing the surface area.

densification front, measured to be 20, 130, and 400 ns for the copper, equiaxed steel, and steel fiber powders, respectively. This increase is linked to the particle/void size, in agreement with earlier experiments on PTFE and mesoscale simulations of wave front character by Eakins [7, 8]. Similar mesoscale simulations are planned for the current powder systems.

SUMMARY

Multi-target plate impact experiments are being conducted to investigate the effect of powder morphology on the densification response of metal powders. A dedicated target fixture has been designed to allow simultaneous loading of three distinct metal powders, and precise measure of the shocked state. Measured states for the equiaxed- and fiber-shaped stainless steel approached crush strengths of 2 and 1.5 GPa, respectively, and were described reasonably well by a configuration-dependent densification model. The equiaxed copper densified at a higher stress than predicted by the same model, which is thought to be due to its irregular morphology and corresponding increased surface area. These results demonstrate the dependence of dynamic densification on particle morphology and the need for further experiments over a broad range of powder configurations.

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