Conference Proceedings of the Society for Experimental Mechanics Series

Sharlotte L.B. Kramer
Rachael Tighe *Editors*

Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 7

Proceedings of the 2020 Annual Conference on Experimental and Applied Mechanics

SEM

Springer

Conference Proceedings of the Society for Experimental Mechanics Series

Series Editor

Kristin B. Zimmerman
Society for Experimental Mechanics, Inc.,
Bethel, CT, USA

The Conference Proceedings of the Society for Experimental Mechanics Series presents early findings and case studies from a wide range of fundamental and applied work across the broad range of fields that comprise Experimental Mechanics. Series volumes follow the principle tracks or focus topics featured in each of the Society's two annual conferences: IMAC, A Conference and Exposition on Structural Dynamics, and the Society's Annual Conference & Exposition and will address critical areas of interest to researchers and design engineers working in all areas of Structural Dynamics, Solid Mechanics and Materials Research.

More information about this series at http://www.springer.com/series/8922

Sharlotte L.B. Kramer • Rachael Tighe
Editors

Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 7

Proceedings of the 2020 Annual Conference on Experimental and Applied Mechanics

Springer

Editors
Sharlotte L.B. Kramer
Sandia National Laboratories
Albuquerque, NM, USA

Rachael Tighe
University of Waikato
Hamilton, New Zealand

ISSN 2191-5644 ISSN 2191-5652 (electronic)
Conference Proceedings of the Society for Experimental Mechanics Series
ISBN 978-3-030-59863-1 ISBN 978-3-030-59864-8 (eBook)
https://doi.org/10.1007/978-3-030-59864-8

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

Residual Stress, Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials represents one of seven volumes of technical papers to be presented at the 2020 SEM Annual Conference and Exposition on Experimental and Applied Mechanics organized by the Society for Experimental Mechanics scheduled to be held in Orlando, FL, September 14–17, 2020. The complete proceedings also include volumes on: *Dynamic Behavior of Materials; Challenges in Mechanics of Time-Dependent Materials, Fracture, Fatigue, Failure and Damage Evolution; Advancement of Optical Methods & Digital Image Correlation in Experimental Mechanics; Mechanics of Biological Systems and Materials, Micro- and Nanomechanics & Research Applications; and the Mechanics of Composite, Hybrid & Multifunctional Materials.*

Each collection presents early findings from experimental and computational investigations on an important area within experimental mechanics; residual stress, thermomechanics, and infrared imaging inverse problem methodologies; and the mechanics of additive and advanced manufactured materials being a few of these areas.

In recent years, the applications of infrared imaging techniques to the mechanics of materials and structures has grown considerably. The expansion is marked by the increased spatial and temporal resolution of the infrared detectors, faster processing times, much greater temperature resolution, and specific image processing. The improved sensitivity and more reliable temperature calibrations of the devices have meant that more accurate data can be obtained than were previously available.

Advances in inverse identification have been coupled with optical methods that provide surface deformation measurements and volumetric measurements of materials. In particular, inverse methodology was developed to more fully use the dense spatial data provided by optical methods to identify mechanical constitutive parameters of materials. Since its beginnings during the 1980s, creativity in inverse methods has led to applications in a wide range of materials, with many different constitutive relationships, across material heterogeneous interfaces. Complex test fixtures have been implemented to produce the necessary strain fields for identification. Force reconstruction has been developed for high strain rate testing. As developments in optical methods improve for both very large and very small length scales, applications of inverse identification have expanded to include geological and atomistic events. Researchers have used in situ 3D imaging to examine microscale expansion and contraction and used inverse methodologies to quantify constitutive property changes in biological materials.

Mechanics of additive and advanced manufactured materials is an emerging area due to the unprecedented design and manufacturing possibilities offered by new and evolving advanced manufacturing processes and the rich mechanics issues that emerge. Technical interest within the society spans several other SEM technical divisions such as composites, hybrids and multifunctional materials, dynamic behavior of materials, fracture and fatigue, residual stress, time-dependent materials, and the research committee.

The topic of mechanics of additive and advanced manufacturing included in this volume covers design, optimization, experiments, computations, and materials for advanced manufacturing processes (3D printing, micro- and nano-manufacturing, powder bed fusion, directed energy deposition, etc.) with particular focus on mechanics aspects (e.g., mechanical properties, residual stress, deformation, failure, rate-dependent mechanical behavior).

Albuquerque, NM, USA Sharlotte L.B. Kramer
Hamilton, New Zealand Rachael Tighe

Contents

The original version of this book was revised. The incorrect spelling of the second editors first name has been updated. The correction is available at https://doi.org/10.1007/978-3-030-59864-8_17

Chapter 1
Visualization and Simulation of Particle Rearrangement and Deformation During Powder Compaction

Marcia A. Cooper, Joel T. Clemmer, Michael S. Oliver, Dan S. Bolintineanu, and Jeremy B. Lechman

Abstract Two key mechanical processes exist in the formation of powder compacts. These include the complex kinematics of particle rearrangement as the powder is densified and particle deformation leading to mechanical failure and fragmentation. Experiments measuring the time varying forces across a densifying powder bed have been performed in powders of microcrystalline cellulose with mean particle sizes between 0.4 and 1.2 mm. In these experiments, diagnostics measured the applied and transmitted loads and the bulk powder density. Any insight into the particle behavior must be inferred from deviations in the smoothly increasing stress-density compaction relationship. By incorporating a window in the compaction die body, simultaneous images of particle rearrangement and fracture at the confining window are captured. The images are post-processed in MATLAB® to track individual particle motion during compression. Complimentary discrete element method (DEM) simulations are presented and compared to experiment. The comparison provides insight into applying DEM methods for simulating large or permanent particle deformation and suggests areas for future study.

Keywords Granular material · Compression · Fracture · Discrete element method · Imaging

1.1 Introduction

Granular materials are commonly processed for applications ranging from pharmaceuticals, to structural materials, to energy storage. Much of the literature data reports experimental compaction curves obtained at slow compression rates on materials where the particles have specific size, morphology, and surface characteristics. However, the compaction behavior of a granular material is strongly dependent on individual particle strength and characterization of the particle mechanics. Few models have incorporated representations of particle strength [1–3], while other particle characteristics of morphology and surface roughness are largely ignored. Computational methods including discrete element method (DEM) [4] and peridynamics [5] offer new capabilities in improved modeling treatments of granular materials in compression. Our efforts are aimed at developing a multi-scale, computational-experimental approach to create novel capabilities enabling process-structure-property-performance design and optimization of powder compacts.

Uniaxial and triaxial confined compression data of powders are common in the experimental literature. In compression, the processes of particle rearrangement, local elastic and plastic deformation, and fragmentation are all present to varying levels as determined by particle characteristics of strength, size, and shape. These levels often must be inferred from bulk measurements of boundary forces and bed volume. Previous experiments have visualized stress networks in optically accessible experiments [6]. The advancement of X-ray methods is affording new opportunities for particle visualizations in 3D [7–9]. However, current micro-computed tomography (micro-CT) technology has relatively large voxel sizes and long scan time durations that limit its usefulness to many particle systems of industrial interest.

Our research began with uniaxial confined compressions in a traditional cylindrical apparatus with microcrystalline cellulose (MCC) particles of different mean size [10]. We seek to avoid some of the immediate challenges of micro-CT imaging

M. A. Cooper (✉) · M. S. Oliver
Explosive Technologies, Sandia National Laboratories, Albuquerque, NM, USA
e-mail: macoope@sandia.gov

J. T. Clemmer · D. S. Bolintineanu · J. B. Lechman
Engineering Sciences, Sandia National Laboratories, Albuquerque, NM, USA

S. L.B. Kramer, R. Tighe (eds.), *Thermomechanics & Infrared Imaging, Inverse Problem Methodologies and Mechanics of Additive & Advanced Manufactured Materials, Volume 7*, Conference Proceedings of the Society for Experimental Mechanics Series, https://doi.org/10.1007/978-3-030-59864-8_1

during compression and instead simply apply optical access to our benchtop compression apparatus. This enables high-definition (HD) imaging of the particles during all compression regimes with adequate temporal resolution. Post-processing of the particle motion as viewed along the optically-accessible boundary is useful for correlating to particle simulations across the regimes of particle compression including fracture and crushing.

Granular systems are often simulated using the discrete element method. These models represent the system as a discrete collection of interacting particles. There are many varieties of DEMs and the fundamental particles can take on a wide range of shapes and sizes that interact via many different forces. Here, we present some initial DEM results using a model that represents the experimental compression apparatus dimensions and MCC particles. The DEM simulations were run using LAMMPS, a collection of parallel algorithms for the numerical integration of particle dynamics [4]. Model treatments for representing particle deformation and fracture are explored. Ultimately, our goal is to relate macroscale behavior (constitutive model) to particle characteristics as well as process to properties to structure.

1.2 Granular Materials

MCC particles consisted of Vivapur® MCC Spheres of type 350 and 1000 from JRS PHARMA (Weissenborn, Germany). The Vivapur® 350 (Batch No. 5135073146 X), and Vivapur® 1000 (Batch No. 5100070317 X) are referred to as V350 and V1000, respectively. Particle size distributions were measured with a Beckman Coulter LS 13320 laser diffraction particle size analyzer with 50% of the particle size distribution equal to 0.473 ± 0.006 mm (V350) and 1.163 ± 0.128 mm (V1000). The particle shapes are roughly spherical and have internal porosity typically in form of a single void as shown in the images of Fig. 1.1. Water content in the particles was measured by drying under vacuum at 105 °C for 24 h and was nominally constant at 4.5%. Literature values for MCC report a value of the elastic modulus of 7.5 GPa [11].

1.3 Compression Apparatus with Optical Access

The MCC particles are compressed uniaxially in a load-controlled manner by the apparatus of Fig. 1.2. The apparatus consists of a pneumatic cylinder (Bimba Flat-I, Model FOS-1251.5-4GLV) to apply force to the top of a confined powder sample. A support structure vertically aligns the axis of the pneumatic cylinder to the axis of the confined sample. The sample is confined by the rectangular walls of the compression die body and confined axially by an upper and lower ram. Three walls of the compression die body are formed by a 304 stainless steel channel with height of 3.81 ± 0.02 cm, wall thickness of 1.91 ± 0.02 cm, and an inner channel that is 0.660 ± 0.02 cm square and machined for a loose slip fit to the square portion of the upper and lower rams. The fourth side of the confiner was 1.588 ± 0.02 cm thick borosilicate glass secured in place with

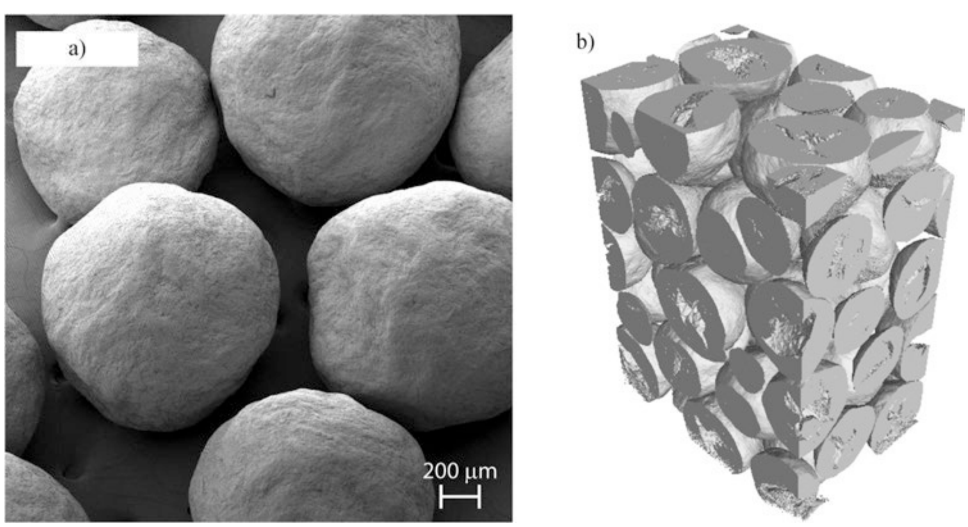

Fig. 1.1 Scanning electron microscope (**a**) and micro-CT image (**b**) of V1000 particles showing nearly spherical particle shape and the existence of a single, large internal void

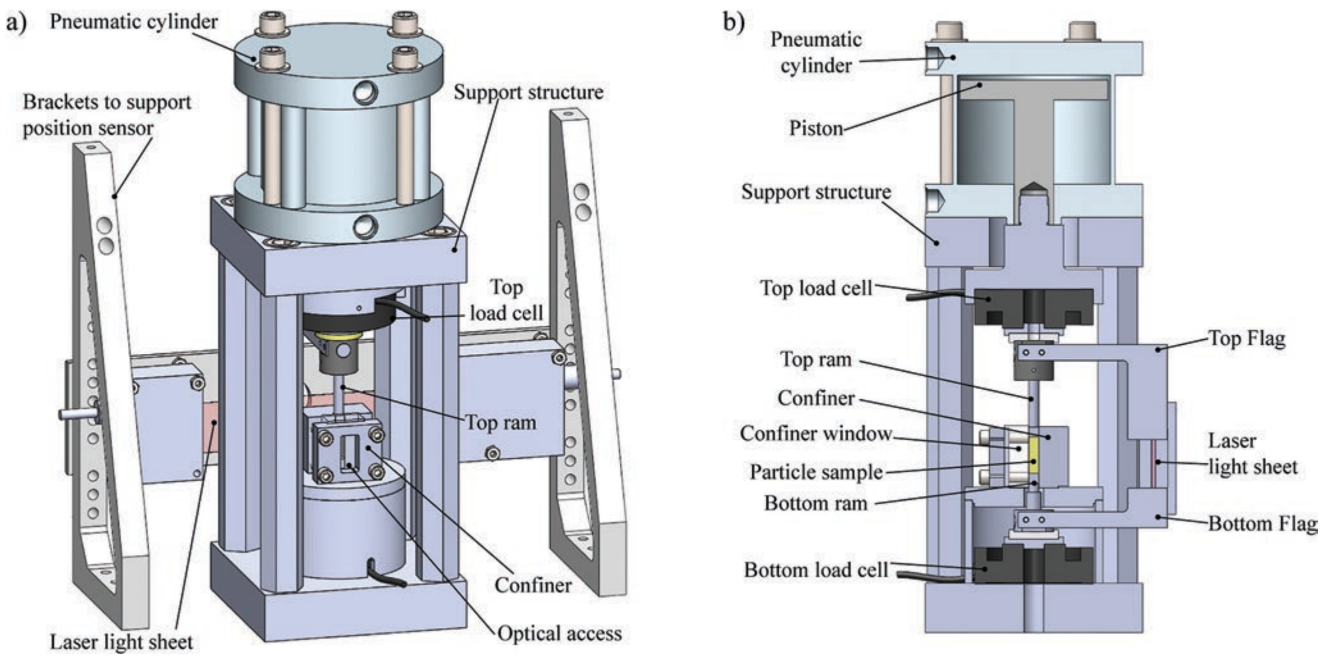

Fig. 1.2 Illustration of the compression apparatus with optical access. (**a**) Isometric view. (**b**) Side view in cross section

a 0.953 ± 0.02 cm thick stainless-steel clamp which had a machined window that provided optical access to the test sample located in the inner channel. To cushion the interface between the confiner window and metal surfaces, one layer of 68.6-μm-thick Kapton tape was used and included in the inner channel dimensions. The upper and lower rams are 304 stainless steel square bars machined to 0.645 ± 0.02 cm square to fit the inner channel of the confiner. The load cell end of each ram was turned to 0.643 ± 0.02 cm to mate to the load cell adapters. The lower ram is stationary while the position and force of upper ram is controlled by pressure within the pneumatic cylinder.

Each test began with a partially assembled compression apparatus by positioning the confiner/window body and lower ram onto the lower load cell (Transducer Techniques, Model THD-5 K-T-OPT-HT). The sample material is weighed and poured into the confiner channel. For most tests, a carbide tipped hand held engraving tool (like McMaster Carr Part No. 1613 T2) was used to vibrate the setup in order to settle the particles. The carbide tip was held against the plate the confiner rested on for a period of at least 30 s. Then, the upper ram is installed at the upper load cell (Transducer Techniques, Model THD-5 K-T-OPT-HT) and plunger of the pneumatic piston such that it was elevated above the top surface of the particulate sample. The downward motion of the upper ram was initiated and the distance between the ram-mounted flags (Fig. 1.2b) decreased as measured by the laser micrometer (Micro-Epsilon, Model 2500). Pressurization of the pneumatic piston is controlled with a LabView program and a voltage-controlled pressure regulator (Proportion-Air Model QB1SSFEE500) resulting in a constant rate of load applied by the upper ram. Force on the particulate sample increased at the preprogramed loading rate until the maximum load was achieved. The force was applied at a rate of 0.22 kN/min resulting in a varying displacement rate during compression nominally between 0.01 mm/s and 0.0001 mm/s. The maximum applied load was determined by the pneumatic cylinder's maximum pressure rating of 1.4 MPa and was connected to bottled air. The LabView program controlled the maximum applied force to 6.7 kN. During a test, the LabView program controlled the pneumatic cylinder pressurization and recorded the laser micrometer sensor and load cell data at a rate of 1 Hz. The maximum force was held for 5 min and then released.

Figure 1.3 plots the compression curve data from the compression apparatus with optical access (Fig. 1.2) with the data from a cylindrical compression apparatus [10]. The data from the different compression experiments show good agreement in terms of applied stress and strain (Fig. 1.3a). When plotted in terms of relative density and applied stress in a linear-log plot (Fig. 1.3b), the new data from the optical compression apparatus begins at a lower tapped density. This is consistent with prior testing and is a trend with the aspect ratio (initial bed height/length scale of confiner cross section) of the powder bed [10]. The average aspect ratio for the data of Fig. 1.3 is 2.1 (cylindrical) and 1.2 (optical).

Video of each experiment was captured using a 2.1-megapixel HD CVI cube camera adapted to a K-Series long distance video microscope lens and recorded in HD format. Fiber-light illumination was directed into the side of the confiner window. Image size was 1920 × 1080 pixels and image magnification of nominally 152.5 px/mm. Frames extracted from a movie compressing V1000 particles appears in Fig. 1.4. MCC particle fracture and crushing was observed earlier in the compres-