J. dynamic behavior mater. (2017) 3:151–155
DOI 10.1007/s40870-017-0120-8

FOREWORD

Foreword to the Special Issue on Ejecta

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Published online: 22 May 2017

Ejecta physics is a young field, having developed over the last 60 years or so. Essentially, ejecta forms as a spray of dense particles generated from the free surface of metals subjected to strong shocks, but the detailed mechanisms controlling the properties of this particulate ejecta are only now being fully elucidated. The field is dynamic and rapidly growing, with military and industrial applications, and applications to areas such as fusion research.

This Special Issue on Ejecta reports the current state of the art in ejecta physics, describing experimental, theoretical and computational work by research groups around the world. While much remains to be done, the dramatic recent progress in the field, some of it first reported here, means that this volume provides a particularly timely review.

In this foreword, we provide a brief historical overview of the development of ejecta physics, to define the context for the work in the rest of this Special Issue.

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A Brief History of Ejecta Physics

1950s and 1960s

There exists anecdotal evidence that ejecta research began in the 1950s, but little of this early research was documented publicly. In Russia, the ejecta phenomenon was first observed in plate impact experiments, and shown to be dependent on the initial surface roughness [1]. The Los Alamos PHERMEX radiographic facility was used to study the production and interaction of jets from shocked surfaces, starting from its very first shot in 1963 [2]. By 1969, Bristow and Hyde [3] describe the results of a mature program in the UK using photographic imaging of ejecta processes to infer whether melt had occurred at the surface of shocked materials. They showed that drive nonuniformity and subsurface fragmentation (spall/scabbing) were also contributory factors in determining the nature of ejecta produced.

1970s

The earliest published ejecta research was done by James Asay [4]. Asay went on to develop a non-radiographic ejecta diagnostic, the eponymous Asay foil [5]. Later, he developed a prescriptive model of ejecta, where he associated the amount of mass ejected from a shocked surface to the volume of surface defects, the rise time of the shock impulse, the yield strength of the material, and the phase of the material on release, i.e., liquid or solid [6]; interestingly he also observed that ejecta production was independent over broad ranges to the peak loading stress P_S. Los Alamos National Laboratory (LANL) also became active in the development of ejecta diagnostics, as released by Hopson and Olinger [7].

1980s

In the 80s, more research is reported, most notably from France [8–12]. These were measurements of the ejecta source from shock loaded roughened surfaces of Ta, Sn and Pb-alloys. The diagnostics included soft radiography and the Asay foil technique. Livermore National Laboratory (LLNL) also reported studies of ejecta from shock loaded Pb [13]. In this period we also see the introduction of piezoelectric probes, which were developed as an alternative means of direct measurement of ejecta momentum [14]. The 80s also saw first reports on ejecta transport [15], models for particle drag [16] and on the dynamic sizing of ejecta from shock loaded materials through use of forward Mie scattering techniques and a streak camera [17].

By the end of the 80s, in a period of about 15 years, multiple ejecta source measurement techniques were in use (soft radiography, the Asay foil and piezoelectric probes), ejecta production from solids and liquids had been documented, and initial transport and sizing experiments performed. This research was reported from France, the UK and US.

1990s

During this decade, ejecta research expanded further. Most notably, the first reported dynamic ejecta sizing with Holographic techniques are reported from LANL [18]. We now see reported research from Russia in planar and cylindrical geometries [1], and another report of LLNL research [19].

In [20], Cloutman developed a detailed Monte-Carlo numerical model for ejecta production and transport, based on previous work on the modeling of diesel sprays.

By the end of the 90s we now see reports of ejecta research from France, Russia, the UK and US. The research had focused on measuring the ejecta source term from solid- and melted-metals with radiography and Asay foils, the size of the source from Mie scattering and holographic techniques, and initial studies of ejecta transport in gases. An initial prescriptive source model had been proposed, but no physics model had emerged.

2000s

In the first decade of the 21st century, more diagnostics were developed, and much more work was done on the ejecta source and sizing of the ejecta particles. Notably, understanding the difference between ejecta from solid versus liquid materials became a focus, as Asay had postulated that liquids eject much more mass than do solids, based on his studies of Pb [6]. For these reasons, Sn became an interesting material to study given its accessible phases: shocks from the solid β- to the solid γ-phase, and releasing to either the solid β-phase ($P_S \lesssim 19.5$ GPa), a mixed solid liquid phase ($19.5 \lesssim P_S \lesssim 33$ GPa), a 100% liquid phase ($33 \lesssim P_S \lesssim 50$ GPa), or from β to liquid on shock, and releasing to 100% liquid when $P_S \gtrsim 50$ GPa [21].

Work at LANL validated a new ejecta diagnostic, lithium niobate piezoelectric pins [22], which are compact and lend themselves to use in constricted geometries. The LANL work also began the best controlled study of the ejecta source. That lengthy study, which continues today, focussed on Sn. The work investigated the Sn ejecta source by varying P_S with supported (flyer plates/guns) and unsupported (high explosively driven, HE) shock loading techniques, and by varying the surface finishes [23–31].

There was of course other research at other institutions. For example, ejecta from materials shock loaded with a laser drive were reported [32], where the researchers studied fragmentation of Sn, even capturing the fragments for post experimental reconstruction of the size and fragmentation patterns. Another sizing diagnostic, an optical microscope, was reported in [33]. Direct numerical simulation of ejecta production was first reported in 2004 using molecular dynamics calculations [34, 35], and in 2007 using a continuum code [36].

At the end of the first decade of the 21st century much had been learned about ejecta. Notably, the realization that ejecta production is a special limiting case of Richtmyer-Meshkov instability [37, 38] (RMI) where the Atwood number $A_t = -1$ started to have a strong influence. This had been known in general terms for some time, but the knowledge of how to apply the physics was incomplete.

2010s

The present decade has seen the application of proton radiography to study RM unstable phenomena, and ejecta studies began to focus more on RMI physics and RMI ejecta models; research on RMI models is now extensively reported [39–42].

The implementation of further Monte-Carlo models for modeling ejecta flows has been reported [43–46]. Further, simulations of ejecta formation from the nanometer to centimeter scales was also reported [42, 47]. The effects of shapes of the surface perturbations on the surface perturbations was first reported in [6], but the 2010s also saw the shape of the perturbations on the ejecta source studied with molecular dynamics (MD) simulations [47, 48].

Studies of the ejecta source also continued, with a report of work on Pb [49], and more results from the LANL Sn work [50]. The LANL source term work was extended to ejecta from a second shockwave [51, 52], and the full LANL Sn ejecta set for supported and unsupported shock loading at a single finish was released [53, 54].

The ejecta source and RM sheet breakup has also been studied extensively with MD simulations [55–60], and more research on dynamic particle sizing diagnostics is reported, works that includes holography and Mie scattering [61, 62].

An area of ejecta research beyond the simple ejecta source is now being investigated rather broadly: transport [63], and the investigation of the ejecta sizes is even being studied with transport dynamics [64–66]. Much work on transport is now beginning, including ejecta breakup dynamics in gases [67].

Importantly, out of ejecta research evolved a new approach to diagnose material strength at high strains and strain rates. The idea was first proposed and studied with simulations by Piriz et al. [68, 69]. Experiments based on the Piriz idea with $A_t > 0$, extended to the situation where $A_t = -1$, in the ejecta regime, are reported in [40, 70], and since then the approach has been extensively studied [71, 72].

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