Investigation of dynamic fragmentation of laser shock-loaded tin at different phases with the integrated diagnostic techniques

Tao Xi, Genbai Chu, Bin Zhu, Min Shui, Yongqiang Zhao, Wei Fan, Yuqiu Gu, Jianting Xin, and Weihua He

ARTICLES YOU MAY BE INTERESTED IN

High-energy X-ray radiography investigation on the ejecta physics of laser shock-loaded tin
AIP Advances 9, 085002 (2019); https://doi.org/10.1063/1.5109748

In situ measurement of the particle size distribution of the fragmentation product of laser-shock-melted aluminum using in-line picosecond holography
AIP Advances 6, 025208 (2016); https://doi.org/10.1063/1.4942089

PDV-based estimation of ejecta particles' mass-velocity function from shock-loaded tin experiment
Review of Scientific Instruments 89, 033901 (2018); https://doi.org/10.1063/1.4997365
Investigation of dynamic fragmentation of laser shock-loaded tin at different phases with the integrated diagnostic techniques

Cite as: AIP Advances 9, 075220 (2019); doi: 10.1063/1.5100566
Submitted: 18 April 2019 • Accepted: 16 July 2019 •
Published Online: 29 July 2019

Tao Xi, Genbai Chu, Bin Zhu, Min Shui, Yongqiang Zhao, Wei Fan, Yuqiu Gu, Jianting Xin, and Weihua He

AFFILIATIONS
Science and Technology on Plasma Physics Laboratory, Laser Fusion Research Center, CAEP, Mianyang 621900, China

Electronic mail: jane_xjt@126.com
Electronic mail: heweihua2004@sina.com

ABSTRACT
We investigated the dynamic fragmentation of laser shock-loaded tin to gain insights on the underlying mechanism of this process. In the experiments, tin samples were shock-loaded by nanosecond laser over sequential pressures ranging from 7 GPa to 43 GPa. Integrated diagnostic techniques, including four-frame optical transverse shadowgraph imaging system, soft recovery, and photonic Doppler velocimetry (PDV), were employed. They provide the shape of the ejecta in the dynamic fragmentation process, the recovered ejecta, as well as the loading parameters. These experimental results were compared with those obtained using one-dimensional Lagrangian hydrodynamics simulation. The crossed results over sequential pressures allowed us to gain better insights on the different dynamic fragmentation processes of spall fracture and micro-spalling, which can help develop reliable models for dynamic fragmentation of triangular-wave shocking metals.

© 2019 Author(s). All article content, except where otherwise noted, is licensed under a Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/). https://doi.org/10.1063/1.5100566

I. INTRODUCTION

When shock wave passes through a sample-vacuum interface, the interaction between release wave and reflected rarefaction wave may cause the well-known dynamic fragmentation, spall fracture.\textsuperscript{1,2} This process is accompanied with the nucleation, growth, and coalescence of voids or cracks, which leads to the ejection of one or several layers from the free surface. Moreover, when the shock wave is strong enough such that the sample is melted on compression or release, a cloud of fine droplets is emitted. This phenomenon is known as micro-spalling.\textsuperscript{3,4} Both spall fracture and micro-spalling have attracted much attention in recent years due to their crucial role in both fundamental science and a wide range of engineering applications. Until now, extensive efforts have been dedicated to the study of dynamic fragmentation. Jarmakani et al.\textsuperscript{11} studied the influence of target thickness, laser energy, and pulse duration on vanadium spalling and fragmentation characterization. Dalton et al.\textsuperscript{12} compared the spall strength of single crystal aluminum with high purity, single crystal aluminum alloy of the 1100 series, and aluminum-magnesium alloy with different average grain sizes. They observed that the former exhibited the highest spall strength. Resseguier et al.\textsuperscript{13-18} conducted a series of experiments to explore the micro-spalling process with multiple diagnostics, and all of them confirmed that micro-spalling and spall fracture are distinct phenomena. Xin et al.\textsuperscript{19} suggested that the dominant mechanism of dynamic fragmentation was strongly affected by loading pressures. Researchers at Los Alamos National Laboratory\textsuperscript{20} reported that the quantity and distribution of ejected fragments were mainly reliant on the material phase at shock release.

Regardless of these extensive studies, the underlying mechanisms of the fragmentation has not been understood yet due to the complexity of spalls, which is affected by multiple factors such as machine marks, material voids, loading strain rate, shock wave shape, shock pressure, and so on. This study aims to explore the dynamic fragmentation characterization of tin sample at different phases with the integrated diagnostic techniques.
phases with the integrated diagnostic techniques, including four frames imaging system (high spatial-resolved transverse shadowgraphy), soft recovery and photonic Doppler velocimetry (PDV).

The article is organized as follows. Section II briefly describes the experimental setup. Section III provides the analysis of preliminary simulations for the laser shock-loaded tin. Section IV presents the experimental results and discussion. The important conclusions of this study are highlighted in Section V.

II. EXPERIMENTAL DETAILS

The experiments have been performed on Shenguang-III (SGIII) prototype laser facility at Laser Fusion Research Center in MianYang, China. The samples are tin foils with 500 μm thickness and 5 mm diameter. Their surfaces are polished with a surface roughness average of Ra≤400 nm. A schematic of the experimental setup is shown in Fig. 1. Two high-power pulsed laser beams are used to irradiate the front surface of tin at 45° angle, and both of them are smoothed by continuous phase plate (CPP) to produce a uniform quasi-circular focal spot of ∼2 mm diameter. The laser beams have a quasi-square shape temporal profile, with 0.351 μm wavelength and 3 ns pulse duration. The samples are placed in a vacuum chamber (pressure ~10^{-4} mbar) to avoid laser breakdown in the air before reaching the target surface.

Laser irradiation drives a triangular shock wave into the samples, leading to its dynamic fragmentation. The integrated diagnostic techniques are used to analyze the evolution and consequences of dynamic fragmentation process. Specifically, the four-frame imaging system provides sequential images of the fragments, which were ejected from the free surface of the sample at different delay times after laser shots. All recorded images have a pixel size of 1280×1024, with a magnification of 2.6 μm/pixel and an exposure time of 3 ns minimizing the motion blur. Soft recovery with PMP foam of a low density in 200 mg/cm^3 is performed to collect the debris, which is ejected from the free surface of the sample. The retrieved foam can provide the information about the depth and morphology of the ejecta using computerized tomography. It should be noted that the background between the free surface of the sample and PMP foam is vacuum. Further, PDV is implemented as an auxiliary technique to obtain cross-validation data. This technique is used to measure the free surface velocity, which in turn is used for calculating the loading pressure near the free surface for different laser shots, but with the same parameters of target and laser.

III. PRELIMINARY SIMULATIONS

We developed a one-dimensional (1D) irradiation hydrodynamic code to investigate the dynamic fragmentation of metal

| Shot | Laser energy (J) | Laser intensity (TW/cm^2) | Penetration depth (mm) | V_{exp} (km/s) | V_{sim} (km/s) | V_{shad} (km/s) | P_{sh} (GPa) |
|------|-----------------|---------------------------|------------------------|--------------|--------------|----------------|-------------|
| S1   | 284             | 3.01                      | -                      | 1.08±0.01    | 1.09         | 1.21±0.09      | 13.93       |
| S2   | 478             | 5.07                      | -                      | 1.53±0.02    | 1.48         | 1.56±0.11      | 21.15       |
| S3   | 528             | 5.60                      | -                      | 1.70±0.02    | 1.55         | 1.65±0.07      | 22.13       |
| S4   | 591             | 6.27                      | -                      | 1.77±0.02    | 1.63         | 1.80±0.13      | 23.49       |
| S5   | 975             | 10.35                     | -                      | 2.02±0.02    | 1.99         | 2.30±0.16      | 30.42       |
| S6   | 1044            | 11.08                     | -                      | 2.15±0.01    | 2.01         | 2.42±0.19      | 30.80       |
| S7   | 161             | 1.71                      | 4.37                   | -            | 0.30         | 0.69±0.02      | 7.66        |
| S8   | 188             | 1.99                      | 6.20                   | -            | 0.63         | 0.82±0.01      | 9.66        |
| S9   | 332             | 3.52                      | 4.04                   | -            | 1.20         | 1.18±0.01      | 16.12       |
| S10  | 506             | 5.37                      | 7.43                   | -            | 1.51         | 1.50±0.13      | 21.59       |
| S11  | 1060            | 11.25                     | 11.12                  | -            | 2.01         | 2.15±0.17      | 30.42       |
| S12  | 2227            | 23.63                     | 17.28                  | -            | 2.59         | -              | 42.72       |
tin induced by nanosecond laser. The code is programmed in Lagrangian coordinates. The electron and ion components are treated separately in a fluid approximation and are loosely coupled to each other. The radiation is assumed Planckian and only coupled to the electron fluid. The degree of ionization is determined by Saha model, and the tin sample is modeled using the metallic polynomial equation of state, von Mises constitutive model. Since this code does not incorporate 2D effects such as lateral shock, it is only suitable for 1D simulation.

The important experimental parameters and diagnostic results are listed in Table I. As mentioned earlier, shadowgraphy and soft recovery techniques are used to observe the dynamic fragmentation process and final state of ejecta, details of which are provided in the next section. The free surface velocities of the sample, which are obtained using PDV ($V_{\text{exp}}$), simulation ($V_{\text{sim}}$), and shadowgraphy ($V_{\text{shad}}$) techniques are in excellent agreement with each other, except for shot S7. This comparison is shown in Fig. 2. The observed discrepancy for S7 may be attributed to the fact that the constitutive model is not suitable for low laser power loading. Further, the free surface velocity $V_{\text{shad}}$ is calculated using the free surface displacement and the delay times between adjacent images. Therefore, the error in average velocity arises due to the extraction of the corresponding pixels in the images, which leads to 0.5% - 8% uncertainties for different shots.

We further analyzed the simulation results to get insights about the detailed dynamic response of the laser-induced material. The evolution of shock wave profile under a laser intensity of 6.27 TW/cm$^2$ is displayed in Fig. 3. When a shock wave passes through sample, its amplitude is decreased, while its pulse width is broadened. However, when shock wave reaches the free surface of the sample, the reflected wave interacts with the unloading wave to produce tensile stress, and this may cause dynamic fragmentation of the material. The inset shows tensile stress distribution in such a case, which can be used to obtain the crucial parameters such as maximum tensile stress.

Moreover, the sample phase significantly affects the material strength, which directly leads to a distinct dynamic fragmentation of the sample. Theoretical pressure-temperature phase diagram for tin is shown in Fig. 4. The typical experimental data and the corresponding release path are also shown in this figure.

IV. EXPERIMENTAL RESULTS

A. Transverse shadowgraphy

Fig. 5 shows the shadowgraphs for typical experimental shots, which are marked as squares in Fig. 4. The successive shadowgraphs show that the response of ejecta varies with the loading pressure. For shot 8 in Fig. 5(a), the sample is mainly in a solid state due to the
low loading pressure, and the shock-induced spall layers and edge rarefaction-induced fracture are clearly visible. As the loading pressure increases, the sample changes to a liquid state. For shots 9-11 as shown in Figs. 5(b)–5(d), the discontinuous boundary changes to continuous boundary gradually, and the interior structure becomes continuous as well. Meanwhile, the micro-jetting, which are primarily governed by the roughness of the free surface and loading pressure, are observed in Fig. 5(c) and Fig. 5(d).
These shadowgraphs show the characteristics of dynamic fragmentation in the sample to some extent, but cannot resolve the interior details of ejecta. To this end, we have employed soft recovery technique, which is discussed in the next subsection.

---

**FIG. 6.** Digital radiography images of the ejecta retrieved within the PMP foam. (a) shot 7, (b) shot 8, (c) shot 9, (d) shot 10, (e) shot 11, (f) shot 12.

**B. Soft recovery analysis**

Soft recovery technique is used to collect the ejecta, thereby providing detailed insights about its interior. Fig. 6 presents the digital radiography images of retrieved foam under different loading pressures. Due to the low shock pressure, the spall layer in Figs. 6(a) and 6(b) can be clearly distinguished. However, in Fig. 6(c), the coexistence of spall layer and spherical droplet suggests that the retrieved ejecta are in the solid-liquid mixing state. When the loading pressure increases further, the spherical droplet becomes the primary ejecta, which implies that liquid state has been achieved. All these observations confirm that the state of the ejecta is closely associated with the loading pressure.

Fig. 6 can also be used to obtain the penetration depth. The relationship between the depth and loading pressure is shown in Fig. 7. It is found that the variation of penetration depth is non-monotonic with the increased loading pressure. Within the release-to-solid region ($P_{sb} \leq 10\, \text{GPa}$), the penetration depth shows a continuous increase with increasing pressure. Similar variation tendency is also observed within the release-to-melt region ($P_{sb} > 21\, \text{GPa}$), and higher penetration depth is obtained in this region than that within the release-to-solid region. However, when the sample is shocked to mixed solid/liquid state (e.g. $P_{sb} = 16.12\, \text{GPa}$), the penetration depth shows an obvious decrease. This variation tends to imply that the breakout pressure as well as the induced state of the sample has great influence on the value of the penetration depth.

---

**V. CONCLUSIONS**

The spall fracture and micro-spalling induced by laser shock-loading have been comprehensively investigated with integrated diagnostic techniques and theoretical simulations. The agreement among free surface velocities obtained using time-resolved PDV, transverse shadowgraphy, and simulations proves the reliability of the latter. The analysis of optical shadowgraph and recovered PMP foam shows that the characteristics of ejected fragments are
primarily governed by the material phase. In future, further characterization of the mass and size distribution of ejecta will be carried out using 3D reconstruction technique.

ACKNOWLEDGMENTS

This work is supported by the Foundation of Science and Technology on Plasma Physics Laboratory (Grant No. 9140C680306150C68298), and the National Natural Science Foundation of China (Grant No. 11805177, 11804319). We would like to thank Guanghui Yuan in the Department of Target Science and Facture for fabricating the tin targets, which are used in our experiments. We also thank the staff of the SGIII prototype facility for operating the laser facility.

REFERENCES

1. A. M. He, P. Wang, and J. L. Shao, Comp. Mater. Sci. 98, 271 (2015).
2. X. Chen, J. R. Asay, S. K. Dwivedi, and D. P. Field, J. Appl. Phys. 99, 023528 (2006).
3. E. Moshe, S. Eliezer, A. Dekel, A. Ludmirsky, Z. Henis, M. Werdiger, and I. B. Goldberg, J. Appl. Phys. 83, 4004 (1998).
4. S. W. Zhang, C. L. Liu, and Q. Z. Li, Chin. J. High Pressure Phys. 22, 125 (2008).
5. B. Glam, S. Eliezer, D. Moreno, L. Perelmutter, M. Sudai, and D. Eliezer, Int. J. Fract. 163, 217 (2010).
6. J. E. Franzkowski, G. Prudhomme, P. Mercier, S. Lauriot, E. Dubreuil, and L. Berthe, Rev. Sci. Instrum. 89, 033901 (2018).
7. G. Seisson, G. Prudhomme, P. A. Frugier, D. Hébert, E. Lescoute, A. Sollier, L. Videau, P. Mercier, M. Boustie, and L. Berthe, Int. J. Impact Eng. 91, 68 (2016).
8. L. Signor, T. D. Rességuié, A. Dragon, G. Roy, A. Fanget, and M. Faessel, Int. J. Impact Eng. 37, 887 (2010).
9. M. Z. Xiang, H. B. Hu, and J. Chen, J. Appl. Phys. 113, 144312 (2013).
10. W. H. He, J. T. Xin, G. B. Chu, J. Li, J. Shao, F. Lu, M. Shui, F. Qian, L. F. Cao, P. Wang, and Y. Q. Gu, Opt. Express 22, 031924 (2014).
11. H. Jarmakani, B. Maddox, C. T. Wei, D. Kalantar, and M. A. Meyers, Acta Mater. 58, 4604 (2010).
12. D. A. Dalton, D. L. Worthington, P. A. Sherer, N. A. Pedrazas, H. J. Quevedo, A. C. Bernstein, P. Rambo, J. Schwarz, A. Edens, M. Geissel, I. C. Smith, E. M. Taleff, and T. Dittmire, J. Appl. Phys. 110, 103509 (2011).
13. E. Lescoute, T. D. Rességuié, J. M. Chevalier, D. Loison, J. P. Cuq-Lelandais, M. Boustie, J. Brel, P. H. Maire, and G. Schurtz, J. Appl. Phys. 108, 093510 (2010).
14. T. D. Rességuié, L. Signor, A. Dragon, M. Boustie, G. Roy, and F. Llorca, J. Appl. Phys. 101, 013506 (2007).
15. T. D. Rességuié, L. Signor, A. Dragon, P. Severin, and M. Boustie, J. Appl. Phys. 102, 073533 (2007).
16. T. D. Rességuié, E. Lescoute, A. Sollier, G. Prudhomme, and P. Mercier, J. Appl. Phys. 115, 043525 (2014).
17. M. Laurençon, T. D. Rességuié, D. Loisonc, J. Baillargeata, J. N. D. Ngnekoua, and Y. Nadota, Mater. Sci. Eng. A 748, 407 (2019).
18. T. D. Rességuié, L. Signor, A. Dragon, M. Boustie, and L. Berthe, Appl. Phys. Lett. 92, 131910 (2008).
19. T. D. Rességuié, L. Signor, A. Dragon, M. Boustie, and L. Berthe, Appl. Phys. Lett. 92, 131910 (2008).
20. M. B. Zellner, W. V. McNeil, J. E. Hammerberg, R. S. Hixson, A. W. Obst, R. T. Olson, J. R. Payton, P. A. Rigg, N. Routley, G. D. Stevens, W. D. Turley, L. Veeser, and W. T. Butler, J. Appl. Phys. 103, 123502 (2008).
21. J. C. Boettger and D. C. Wallace, Phys. Rev. B 55, 2840 (1997).
22. F. Buy, C. Voltz, and F. Llorca, AIP Conf. Proc. 845, 41 (2006).
23. J. N. Johnson, D. B. Hayes, and J. R. Asay, J. Phys. Chem. Solids 35, 501 (1974).