Materials Letters 354 (2024) 135372

Contents lists available at ScienceDirect

Materials Letters

journal homepage: www.elsevier.com/locate/matlet

Flash X-ray radiography of internal damage in soft cellular materials during instrumented dynamic penetration

Tomáš Fíla [a,1,*], Jan Falta [a], Petr Koudelka [a], Jan Šleichrt [a], Nela Krčmářová [a], Isabel Duarte [b]

[a] Czech Technical University in Prague, Faculty of Transportation Sciences, Konviktská 20, 110 00 Prague, Czech Republic
[b] Centre for Mechanical Technology and Automation, Intelligent Systems Associate Laboratory, Department of Mechanical Engineering, University of Aveiro, 3810-193 Aveiro, Portugal

ARTICLE INFO

Keywords:
Flash X-ray
High-speed X-ray radiography
Dynamic penetration
Internal damage
Closed-cell aluminum foam
Direct impact Hopkinson bar

ABSTRACT

Processes of internal damage development during localized dynamic penetration represent a crucial mechanism important for relevant analysis of deformation and failure of plates and sandwich panels under high strain rate conditions. Soft cellular materials are of special importance as the internal damage defines mode of collapse and energy absorption capabilities. In this paper, a fast X-ray radiography is employed for in-situ analysis of the internal damage development in soft closed-cell aluminum foam subjected to a localized high strain rate penetration using an instrumented projectile in a direct impact Hopkinson bar apparatus. The process with a typical duration of a few milliseconds is visualized using four X-ray projections acquired using a flash X-ray system and a high-speed camera. Internal damage such as cracking, shear failure in the vicinity of the projectile, and compaction of the material is successfully identified. This unique method utilizing a laboratory based X-ray source allows for characterization of the penetration mechanism that has been usually analyzed only in post-mortem state.

1. Introduction

Soft cellular materials represent a type of complex heterogeneous materials with applications in a variety of engineering fields, e.g., cushioning, vibration damping, filtration or as fillers for impact energy absorption layers. Closed-cell metal foams represent typical materials for this field and their performance at high strain rates have been studied extensively. Special attention has been paid to strain rate sensitivity, inertia effects, wave propagation, representative volume element, and dynamic compaction. However, localized dynamic penetration, which represents a crucial mode of deformation, has been studied only in a limited number of papers. The damage processes and energy absorption were studied experimentally [1] and numerically [2] including introduction of theories and modelling approaches for interactions at the interface between the foam and the projectile, and for dynamic compaction under the projectile. An important study was published by Pang [3] where partially cut specimens of metal foam were subjected to dynamic indentation using an instrumented projectile and the process was observed by a high-speed camera. Another approach for pre- and post-mortem analysis of the specimens by X-ray computed tomography was employed in [4]. The most limiting factor of all the referenced studies consists in a fact that development of the internal damage was not observed in-situ during the experiment or that the process was not true localized indentation of an intact material. Here, an experimental technique allowing for high-speed in-situ visualization of the internal damage together with measurement of force and velocity of the projectile is required for tracking and identification of the penetration stages, which is a crucial step for representative analysis and modelling.

X-ray radiography represents an ideal method for volumetric inspection, visualization, and characterization of internal damage in materials. In the field of impact dynamics, particle accelerators like synchrotrons have been used for high-speed X-ray imaging of dynamic processes [5]. Moreover, flash X-ray systems have been introduced and employed particularly for visualization of penetration in armament and ballistic protection applications [6] or high-velocity gas-gun experiments [7]. Flash X-ray systems provide advantages over synchrotrons such as large field of view, high penetration depth, accessibility and radiation safety with a cost of sacrificing image quality, resolution and continuous nature of the imaging. In this paper, we use flash X-ray system in a new methodology, where the X-ray system is coupled with a

* Corresponding author.
E-mail address: fila@fd.cvut.cz (T. Fíla).
[1] Present address: Czech Technical University in Prague, Faculty of Transportation Sciences, Konviktská 20, 110 00 Prague, Czech Republic.

https://doi.org/10.1016/j.matlet.2023.135372
Received 4 July 2023; Received in revised form 20 September 2023; Accepted 7 October 2023
Available online 12 October 2023
0167-577X/

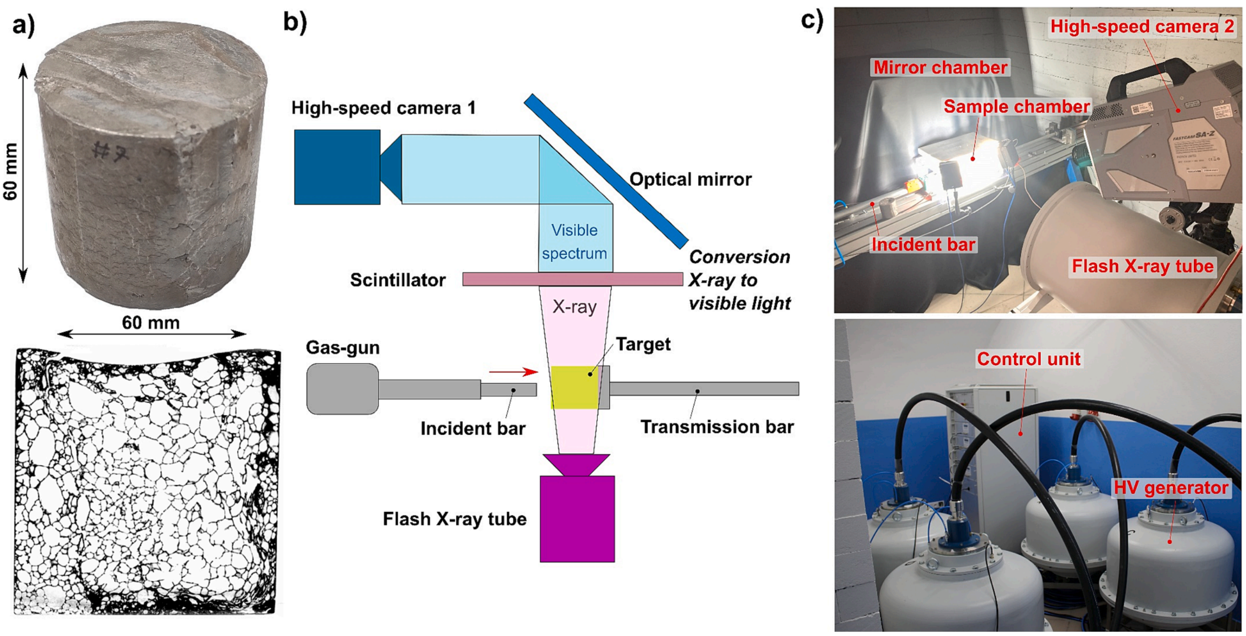

Fig. 1. a) specimen and its axial cross-section, b) principle of the flash x-ray radiography in a split Hopkinson bar, c) experimental setup.

direct impact Hopkinson bar (DIHB) for visualization of the internal damage during localized dynamic indentation into closed-cell aluminum foam. Combination of the fast X-ray radiography and instrumented projectile in a dynamic penetration experiment allows for an unprecedented in-situ visualization of the deformation processes and identification of the penetration stages together with effects of structural imperfections on overall deformation response.

2. Materials and methods

2.1. Material

Cylindrical specimens of closed-cell aluminum alloy (AlSi7) foam having 60 mm in diameter and 60 mm in height (Fig. 1a) were prepared using the powder-compact foaming technique as described in [8]. Each cylindrical foam specimen was prepared by placing the profiles of precursor material (composition: AlSi7 + 0.5 wt% TiH_2; mass: ~125 g) into the cavity (60 mm in length and 60 mm in diameter) of a stainless-steel closed mold inside a pre-heated furnace at 750 °C. After filling the cavity by liquid AlSi7 foam (~12 min), the mold was removed from the furnace and cooled in air, resulting in a solid foam with closed cells covered by an outer dense AlSi7 thin skin. In total, 6 specimens were manufactured and tested together with micro-CT inspection prior to mechanical testing to obtain pore statistics and determine porosity yielding approximately 66 % as an average from all the samples.

2.2. Direct impact Hopkinson bar and flash X-ray system

The dynamic mechanical experiments were performed using DIHB apparatus. The loading device consisted of two bars with a diameter of 20 mm made of high strength aluminum alloy EN-AW-7075-T6: a projectile with a length of 900 mm housed in the barrel of a gas-gun and a transmission bar with a length of 1600 mm with a cylindrical specimen support with a diameter of 60 mm mounted at its impact face. The transmission bar was equipped with two pairs of strain gauges. The projectile was instrumented by velocity sensors and a speckle pattern for digital image correlation (DIC), which allowed for evaluation of actual force and velocity during the penetration. The experiment was observed by a pair of time-synchronized high-speed cameras Fastcam SA-Z 2100 K (Photron, Japan). One camera was positioned at a 30-degree angle to capture the area of interest within the specimen and random speckle pattern for DIC.

The X-ray imaging was performed using MAT 300-4C (Scandiflash, Sweden) flash X-ray imaging device (Fig. 1b). The system is based on multi-anode flash X-ray tube capable to perform up to four radiographic projections during the experiment (Fig. 1c). Acceleration voltage can be set in the range of 100–300 kV, while target current of 10 kA and pulse width of 20 ns are constant and provided using modified Marx generators. The source uses pencil type tungsten anodes with the focal spot of 1 mm and approximately 25° cone beam. The photons emitted during projection were captured using GPXS (Hamamatsu Photonics, Japan) fast scintillating screen for conversion to visible-light spectrum. The resulting visible-light image was deflected using a flat high-precision optical mirror to the second high-speed camera to protect it from intensive ionizing radiation emitted during the X-ray pulse.

3. Experiment

The specimens were subjected to a localized dynamic penetration using the DIHB. The specimen was mounted at the output bar in front of the barrel of the gas-gun while the penetrating projectile remained partially in the barrel during the experiment. Two impact velocities were used: i) 14 m/s and ii) 26 m/s resulting in impact energy of approximately 88 J and 275 J (initial strain rate of approximately 230 s^{-1} and 430 s^{-1}). Duration of the experiments up to full-stop of the projectile was in range between 8 ms and 15 ms. Time synchronization of all the experimental devices was performed by trigger pulse initiated by the laser gate mounted in front of the barrel. Four flash X-ray projections with equidistant time gaps were taken during each experiment to capture the moment of penetration into the specimen as well as the densification phase of its deformation response. Imaging parameters were optimized to obtain sufficient contrast in the X-ray projections with the resulting acceleration voltage of 150 kV and frame rate of 20 kfps at resolution of 1024 × 1024 px for acquisition of the projection by the high-speed camera according to the decay characteristics of the scintillator.

4. Results and discussion

Mechanical response at the input and the output sides was evaluated

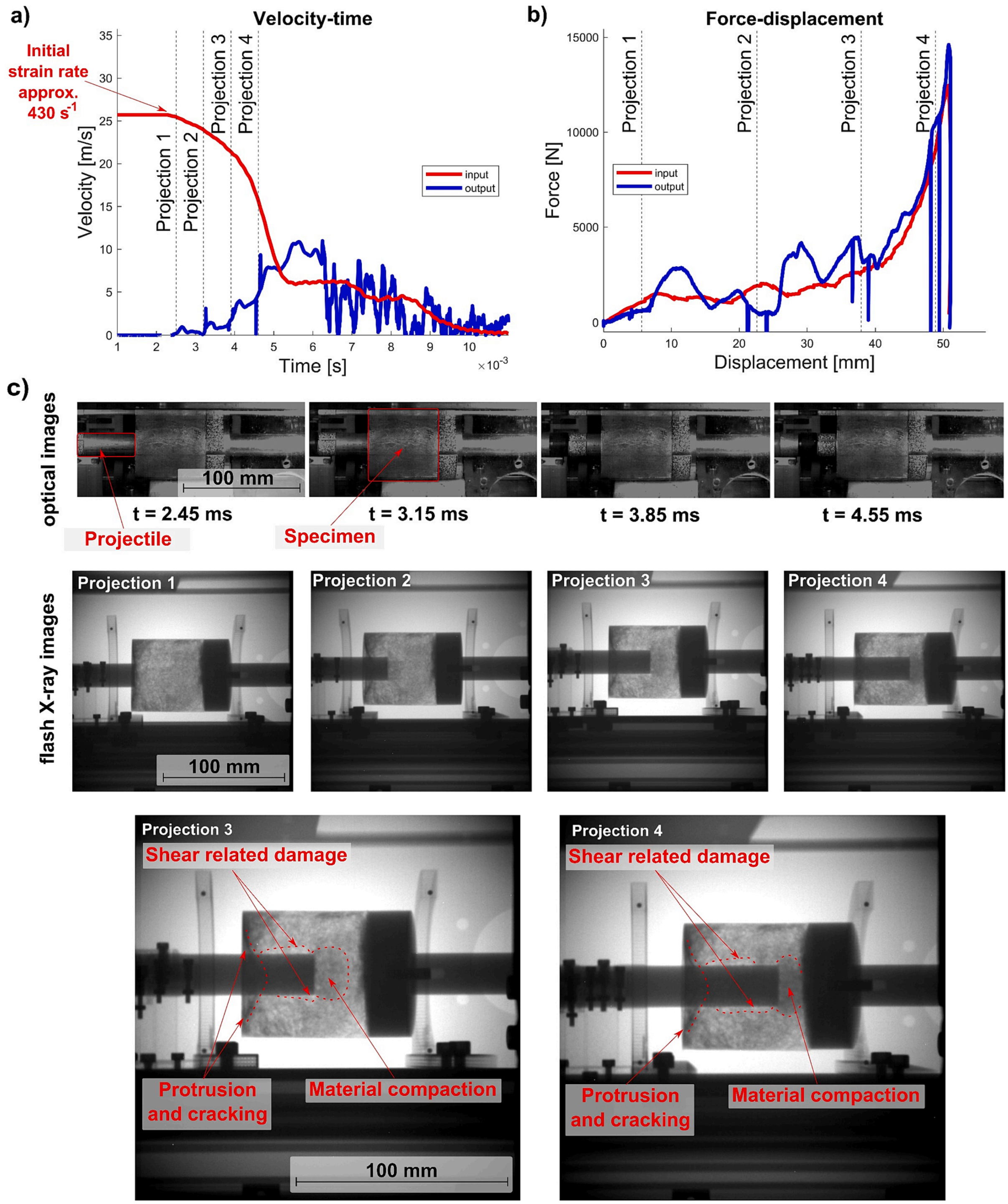

Fig. 2. a) velocity of the projectile and the backside of the specimen during penetration, b) force-displacement diagram, c) high-speed camera images and flash x-ray images taken in the identical time.

from strain gauges, velocity sensors, and DIC using standard wave propagation theory for split Hopkinson bars. Time-synchronized images from the high-speed camera capturing the sample directly in the visible spectrum were compared with the X-ray projections.

Actual impact velocities of the projectile and backside of the specimen are shown in Fig. 2a). Force-displacement diagram of penetration is presented in Fig. 2b). Points, where the individual flash X-ray images were taken, are highlighted in both diagrams. The plots show that the information from the impact side during the penetration is crucial for analysis and cannot be easily replaced by noisy information from the output bar. Standard high-speed camera images and the flash X-ray images taken at the identical times are compared in Fig. 2c). While the images in the visible spectrum cannot provide any information about the internal processes, the defects can be identified in the X-ray images. Protrusion and cracking of the specimen's impact side, shear related damage in pores around projectile and material compaction under the projectile can be identified and their occurrence compared with the mechanical information.

The aim of this study is the in-situ visualization of the internal defects developed during localized dynamic penetration. Strain rate sensitivity, overall mechanical response, statistics and damage theories are beyond the scope of this short report.

5. Conclusions

Flash X-ray system was coupled with the DIHB setup with an instrumented projectile and this assembly was successfully employed to visualize internal defects in the closed-cell aluminum foam during localized dynamic penetration. The introduced experimental technique allowed for identification of internal processes in the foam such as pore damage and material compaction and can further be used as a vital tool for theory definition and modelling.

CRediT authorship contribution statement

Tomáš Fíla: Conceptualization, Methodology, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Funding acquisition. **Jan Falta:** Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Petr Koudelka:** Conceptualization, Methodology, Investigation, Writing – original draft, Writing – review & editing. **Jan Šleichrt:** Conceptualization, Investigation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing. **Nela Krčmářová:** Investigation. **Isabel Duarte:** Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The research was supported by the Czech Science Foundation (project Junior Star no. 22-18033M). The work was also supported by the projects: UIDB/00481/2020 (FCT, PT), UIDP/00481/2020 (FCT, PT) and CENTRO-01-0145-FEDER-022083 (Centro2020, PORTUGAL 2020).

References

[1] G. Lu, J. Shen, W. Hou, D. Ruan, L. Ong, Dynamic indentation and penetration of aluminium foams, Int. J. Mech. Sci. 50 (2008) 932–943, https://doi.org/10.1016/j.ijmecsci.2007.09.006.

[2] H. Xi, L. Tang, S. Luo, Y. Liu, Z. Jiang, Z. Liu, A numerical study of temperature effect on the penetration of aluminum foam sandwich panels under impact, Compos. B Eng. 130 (2017) 217–229, https://doi.org/10.1016/j.compositesb.2017.07.044.

[3] X. Pang, H. Du, Investigation on dynamic penetration of closed-cell aluminium foam using in situ deceleration measurement, Compos. B Eng. 100 (2016) 78–90, https://doi.org/10.1016/j.compositesb.2016.06.040.

[4] J. Šleichrt et al., Dynamic penetration of cellular solids: Experimental investigation using Hopkinson bar and computed tomography, Materials Science and Engineering: A 800 (2021) 140096. URL: https://doi.org/10.1016/j.msea.2020.140096. doi: 10.1016/j.msea.2020.140096.

[5] M.P. Olbinado, et al., Ultra high-speed x-ray imaging of laser-driven shock compression using synchrotron light, J. Phys. D Appl. Phys. 51 (2018), 055601, https://doi.org/10.1088/1361-6463/aaa2f2.

[6] E. Strassburger et al., Flash x-ray cinematography analysis of dwell and penetration of small caliber projectiles with three types of SiC ceramics, Def. Technol. 12 (2016) 277–283. URL: https://www.sciencedirect.com/science/article/pii/S2214914716000271. doi: 10.1016/j.dt.2016.01.011, 2016 International Symposium on Ballistics.

[7] B.E. Schuster et al., Concurrent velocimetry and flash x-ray characterization of impact and penetration in an armor ceramic, Procedia Eng. 103 (2015) 553–560. URL: https://www.sciencedirect.com/science/article/pii/S1877705815007468. doi: 10.1016/j.proeng.2015.04.072, proceedings of the 2015 Hypervelocity Impact Symposium (HVIS 2015).

[8] I. Duarte, M. Vesenjak, M.J. Vide, Automated continuous production line of parts made of metallic foams, Metals 9 (2019) 531, https://doi.org/10.3390/met9050531.