EXPERIMENTAL AND NUMERICAL INVESTIGATION OF NOVEL AL–CENOSPHERE–MWCNT COMPOSITE FOAMS UNDER VARYING STRAIN RATE

Ravi Kumar[a] and Prosenjit Das[a,b*]
[a]Advanced Manufacturing and Materials Processing Laboratory (AMMPL), Department of Materials Engineering, Indian Institute of Science (IISc), Bengaluru, 560012, India
[b]Department of Design and Manufacturing, Indian Institute of Science, Bengaluru-560012, India.
***Email: prosenjitdas@iisc.ac.in**
Tel: +91-80-2293 3776, Fax: +91-80-2360 0472

ABSTRACT

Aluminum-based hybrid foams are emerging as advanced lightweight materials owing to their excellent energy absorption capability, corrosion resistance, and enhanced impact performance, making them highly suitable for aerospace, automotive, and defense applications. In the present study, the strain rate-dependent compressive behavior of in-house developed Novel Al–Cenosphere–MWCNT composite foam fabricated through the stir casting route is investigated under quasi-static and high strain rate loading conditions. The incorporation of hollow ceramic cenospheres significantly reduces density while improving thermal stability, whereas the addition of multi-walled carbon nanotubes (MWCNTs) enhances shock resistance through effective load transfer and energy dissipation mechanisms. The synergistic effect of cenospheres and MWCNTs enables a tailored combination of lightweight characteristics and improved mechanical response. Numerical simulations are carried out using an explicit finite element approach incorporating the Johnson–Cook constitutive model to capture the nonlinear deformation behavior up to strain rates of 1000 s^{-1}. The developed finite element model is validated through experimental compression tests performed using a Universal Testing Machine (UTM) and Split-Hopkinson Pressure Bar (SHPB) setup. A good agreement between experimental and numerical results confirms the predictive capability of the proposed model. The study demonstrates the effectiveness of integrating experimental characterization with numerical modeling for evaluating the dynamic mechanical response of Novel Al–Cenosphere–MWCNT composite foams and highlights their potential for lightweight structural and energy-absorbing applications relevant to casting and advanced material processing industries.

KEYWORDS: ALUMINUM HYBRID FOAM – CENOSPHERES – MULTI WALLED CARBON NANOTUBES (MWCNTS) – HIGH STRAIN RATE COMPRESSION – JOHNSON COOK MODEL – FEM

INTRODUCTION

Lightweight materials with tailored mechanical performance are increasingly important for next-generation engineering structures, where material efficiency must be achieved without compromising functionality [1]. Aluminium foams offer a distinctive combination of low density, specific strength, energy absorption, and structural efficiency, making them attractive for lightweight components and sandwich structures. However, their performance is intrinsically linked to the processing route, alloy/reinforcement composition, and resulting cellular architecture. Controlling these factors remains a key challenge in developing foams with reproducible and application-specific mechanical properties.

In the present work, a novel Al-based hybrid foam reinforced with cenospheres and multi-walled carbon nanotubes (MWCNTs) is developed through a liquid casting route. The study experimentally investigates the influence of composition and strain rate on the dynamic mechanical response of the developed Al–Cenosphere–MWCNT composite foam material. The observed behaviour is further related to the processing conditions, constituent composition, and resulting microstructural characteristics, while numerical simulations are employed to complement the experimental investigation and predict the strain-rate-dependent response. The combined approach provides insights into the development and processing of aluminium hybrid foams with tailored mechanical performance.

MATERIALS AND METHODS

The Al–Cenosphere–MWCNT hybrid foam is fabricated through a liquid casting route, with emphasis on controlling reinforcement incorporation, dispersion, and cellular structure. An Al–Si alloy serves as the matrix, while cenospheres and multi-walled carbon nanotubes (MWCNTs) are incorporated as hybrid reinforcements using stir-casting process. The extremely low density of MWCNTs makes their effective incorporation and dispersion in the molten alloy challenging; therefore, a plunging mechanism is employed to facilitate their introduction into the melt. The processing parameters and reinforcement composition are optimized to obtain a stable and uniform cellular structure, followed by microstructural and pore morphology characterization. The mechanical response is evaluated under quasi-static compression and at different strain rates using a Split Hopkinson Pressure Bar (SHPB). The experimental results are used to determine the Johnson–Cook (J–C) constitutive model parameters [2], which are implemented in numerical simulations. The simulated deformation and stress–strain responses are compared with the experimental results to evaluate the model's capability in predicting the strain-rate-dependent behaviour of the developed hybrid foam.

RESULTS AND DISCUSSIONS

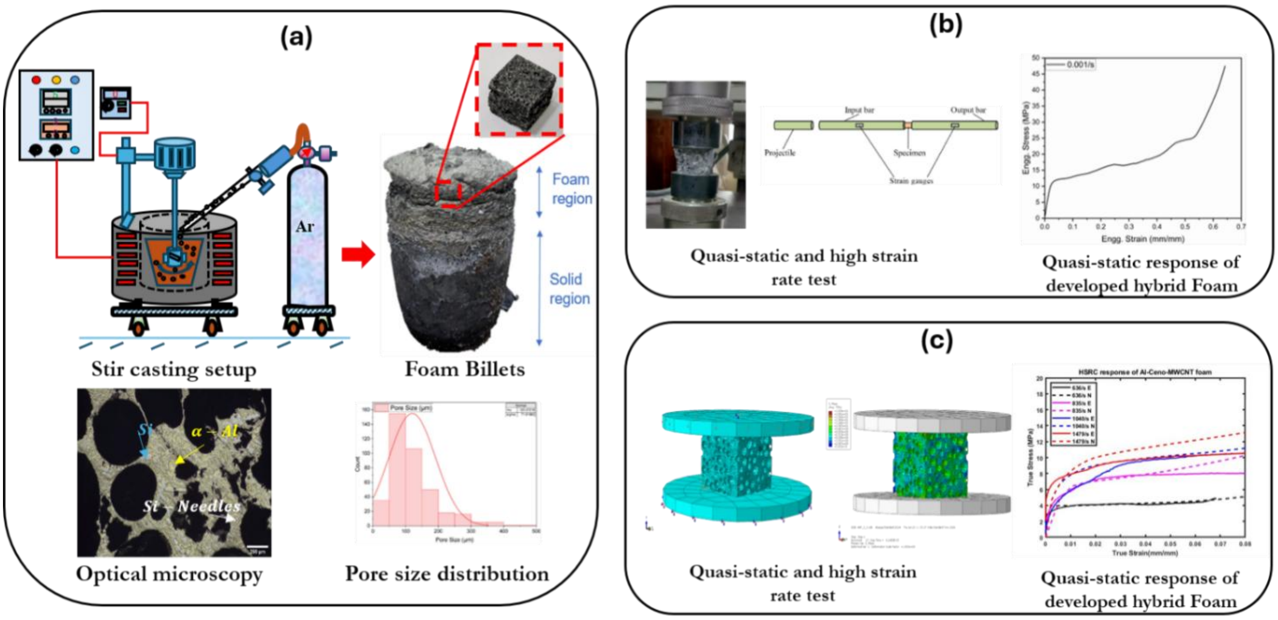

Fig.1 – Overview of (a) foam fabrication and characterization, (b) compression testing, and (c) FE simulation

As shown in Fig. 1 (a), the Al–Cenosphere–MWCNT hybrid foam is successfully fabricated with a density of 1.12 g/cm³, 65% porosity, and an average pore radius of 185 μm. Microscopy shows predominantly circular pores with distinct Al and Si phases. As shown in Fig. 1 (b), quasi-static compression gives a modulus value of 445 MPa, plastic collapse stress of 10 MPa, plateau stress of 15 MPa, and densification strain of 0.5. Although Al–Si alloys are generally strain-rate insensitive, the developed foam exhibits positive strain-rate sensitivity. As shown in Fig. 1(c), the foam RVE based FEM model, using J–C model parameters obtained from SHPB results, shows good agreement with the experimental response, particularly up to the plateau region, demonstrating the model's capability to capture the primary compressive behaviour.

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