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Microstructure-based experimental and numerical investigations on the sound absorption property of open-cell metallic foams manufactured by a template replication technique

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HIGHLIGHTS

- Open-cell IN625 foams with variable porosity and pore size were produced by a newly developed template replication method.
- There was a linear correlation between the average pore size of the polymeric templates and the produced IN625 foams.
- It indicates the advantage of microstructure controllability of the template replication method.
- Sound absorption coefficient of IN625 foams was predicted using measureable microstructure parameters via FP and DB models.
- IN625 foam with $\alpha > 0.9$ at $f > 1500$ Hz of 50 mm thickness has been successfully fabricated and accurately predicted.

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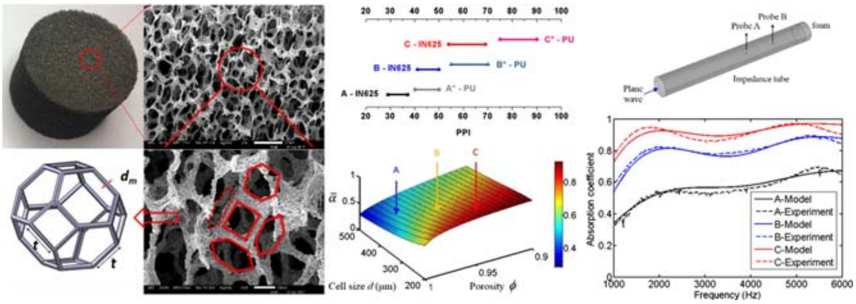
GRAPHICAL ABSTRACT



ABSTRACT

The current study investigates the acoustic absorption property of nickel-based superalloy open-cell foams manufactured by a newly developed template replication process. Inconel 625 open cell foams with controllable porosities (92%–98%) and cell sizes (300 μm–900 μm) have been successfully produced and tested for their sound absorption performance. It is evident that foam samples with the smallest cell size among them exhibit the best acoustic absorption performance, with sound absorption coefficient > 0.9 at frequencies >1500 Hz for 50 mm thick sample. In the numerical simulation, the classical Delany-Bazley model is employed to predict the acoustic absorption property across a broad frequency range, and it requires knowledge of foam's static air flow resistivity, which, as proposed in this work, can be analytically expressed as a function of foam's microstructure parameters. A good agreement between such microstructure-based numerical model and experimental results was obtained. The proposed model can be utilized as a material design tool to guide the production of foam with optimal microstructure for sound absorption through the controllable template replication process.

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1. Introduction

Sound absorbers are widely used in various noise control applications such as vehicle mufflers, building ventilation systems, noise enclosures, etc. [1] Recently, the increasing demands from aerospace and marine industry calls for more efficient absorbers with lightweight, high temperature resistant and superior mechanical properties [2]. Ni-based Inconel 625 superalloy has high temperature and corrosion resistance comparing to traditional aluminum, organic and polymer sound absorbing materials, yet possesses high tensile and creep strength comparing to advanced ceramic materials [3]. With open-cell structure, IN625 foam allows the propagation of sound wave through its interconnected cells, whereas in the meantime, gradually absorbs the acoustic energy via a complex combination of mechanisms including viscous loss, thermal loss, mechanical damping, etc. [4]. Additionally, the IN625 foam has high porosity, low density, high surface area-to-volume ratio and high stiffness and strength [5]. These properties make IN625 foam potentially next-generation advanced sound absorbers to meet the increasing demands and challenges.

The sound absorption efficiency of foam material is a highly microstructural-dependent property, therefore a process which can control the microstructure of the metallic foam is preferred. Various technologies, such as replication [5–7], space-holder [8–10] and additive manufacturing technology [11–13], have been developed to fabricate metallic foams with open-cell structures. For the space-holder methods [8–10], it is difficult to control the pore size and distribution of the produced cell structures, because the porous structures are generated by the randomly distributed pore forming particles. Conversely, additive manufacturing technology has the advantages in design and print regular open-cell structures [11–13]. However, it is a high cost process and its application is mainly limited to regular cell pattern and small volume production. A template replication method is recently developed in our group [5], using a new IN625 slurry system and commercially available polymeric foam template. In the process, IN625 slurry is firstly made by ball milling, then coated onto an open-cell polymeric foam template, before subjected to low temperature heat treatment process to burn of the template, and finally sintered in high temperature. The previous result shows that the solid loading of the IN625 slurry affect the mechanical properties of the IN625 foams, and more importantly, the IN625 foams mimic the open-cell morphology of the polymeric template [5]. Therefore, this process has the potential to control the microstructure of the produced foam while selecting suitable template. In this work, the effect of the microstructure properties of the polymeric foam templates on the microstructure and hence sound absorption properties of the IN625 foam will be explored.

The influence of microstructure of foams on their acoustic performance has been studied experimentally [14–16], analytically [17,18] and numerically [19–21]. Han et al. [14] reported that with rigid backing, open-cell Al foam had better sound absorption with relatively small pores, while with an air gap, medium pores were more preferred. Han et al. [15] found the effect of pore size and porosity on sound absorption was non-monotonous and uncertain, while airflow resistance had more direct influence. Considering only airflow resistivity, Delany and Bazley [19] demonstrated reasonable good estimations of sound absorption performance of metal foams using a simplified empirical model (DB model) derived from systematically analyzing a wide range of fibrous sound absorbers. On top of DB model, new semi-phenomenological models [22–25] have been developed by introducing additional microscopic parameters, such as porosity, pore size, viscous and thermal characteristic lengths, et al. Although the accuracy of predictions is improved, such new models become highly complicated, and the involved microscopic parameters are not only difficult to be measured experimentally, but also cross-correlated and not independent. It has been clear that the foam microstructure determines its acoustic absorption property, but only limited investigations have been demonstrated to predict the foam performance using directly measurable microstructure properties.

As a type of macroscopic fluid parameter, airflow resistivity, on the other hand, was reported to be influenced by the microstructure properties of foam [26,27]. Geometrically, the microstructure of metal foams can be characterized as a rectangular distribution of solid material, called Representative Unit Cell (RUC) [28]. Using the concept of RUC and its characteristic lengths as inputs, a theoretical model (FP model) was proposed by Fourie and Plessis [26] to predict the pressure drop in isotropic metal foams. The characteristic dimensions of RUC can be derived by measurable geometrical parameters, upon considering the metal foams as an ordered array of tetrakaidecahedra [26]. The FP model was developed to reveal the fluid parameter of metal foams, but has never been transferred to acoustic study and thus its applicability is unknown. To bridge this gap, we first perform microstructure analysis based on FP model, which yields the airflow resistivity from experimentally measured microstructure geometry, then the result value is fed to DB model for sound absorption prediction. This approach directly connects the microstructure properties to the sound absorption performance of foams, therefore, has significant potential to predict the optimal yet manufacturable foam microstructure design.

In the current study, experimentally, open-cell IN625 foam with variable porosity and pore size were produced by the newly-developed template replication method. A simple linear correlation was found between the microstructure properties of the polymeric templates and the produced IN625 foams, indicating the advantage of the microstructure controllability of the template replication method. Numerically, a link was established between the FP and DB models which enable the prediction of sound absorption coefficient of the IN625 foams using simply microstructure parameters, such as porosity, strut width, strut length, etc., which can be measured experimentally. These microstructure parameters were used as input of the FP model to predict the airflow resistivity, and the result was used as input of the DB model to predict the sound absorption coefficient of the IN625 foams. The predicted and measured sound absorption coefficients show reasonable agreement. A parametric study on the foam parameters was further carried out, indicating that more efficient absorption with optimized microstructure can be achieved by adjusting the manufacturing parameters. An optimized IN625 foam was then fabricated, showing more desired acoustic performance in the test. This work brings closer the relationship of processing (template replication method) - microstructure (foam cell morphology) - properties (acoustic absorption) of metallic foams with tetrakaidecahedra open cell, and advance the understanding of using IN625 high temperature superalloy as high performance sound absorbers.

2. Experimental and numerical methods

2.1. Fabrication of IN625 open cell foams

IN625 open cell foams were fabricated by a template replication method using IN625 slurry as precursor materials and polyurethane (PU) foam as templates [5]. Commercially available polyurethane (PU) foam provided from FoamPartner™ was employed. IN625 slurry was prepared based on a newly developed binder-dispersant-solvent system, using IN625 powders (80%–22 μm, Sandvik Osprey Ltd., UK, chemical composition as shown in Table 1) as raw powders, Butvar® B-98 polyvinyl butyral (PVB) as binder, stearic acid as dispersant and ethyl alcohol (99.9%) as solvent. In the process, first, dispersant (stearic acid, 0.8 g) was added to the ethanol solvent (8 g), and fully dissolved using ultrasonic vibration. IN625 powders (54 g) were slowly added in the above slurry and ball-milled for 4 h in order to break up weak agglomerates. Binder (PVB, 1.75 g) was added for another 20 h ball milling

Table 1
Chemical composition (nominal), % of the IN625 raw powders.

Ni	Fe	C	Cr	Mo	Al	Ti	Nb
Bal.	≤5	≤0.1	22	9	≤0.4	≤0.4	3.5