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Multiobjective optimization for design of multifunctional sandwich panel heat pipes with micro-architected truss cores

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ABSTRACT

A micro-architected multifunctional structure, a sandwich panel heat pipe with a micro-scale truss core and arterial wick, is modeled and optimized. To characterize multiple functionalities, objective equations are formulated for density, compressive modulus, compressive strength, and maximum heat flux. Multiobjective optimization is used to determine the Pareto-optimal design surfaces, which consist of hundreds of individually optimized designs. The Pareto-optimal surfaces for different working fluids (water, ethanol, and perfluoro(methylcyclohexane)) as well as different micro-scale truss core materials (metal, ceramic, and polymer) are determined and compared. Examination of the Pareto fronts allows comparison of the trade-offs between density, compressive stiffness, compressive strength, and maximum heat flux in the design of multifunctional sandwich panel heat pipes with micro-scale truss cores. Heat fluxes up to 3.0 MW/m^2 are predicted for silicon carbide truss core heat pipes with water as the working fluid.

1. Introduction

Multifunctional materials embody several attributes, including some or all of structural, thermal, electrical, and optical aspects, and are emerging as solutions providing decreased volume, mass, and power requirements (Evans et al., 1998). Periodic cellular materials (Wadley, 2006) are known to yield strong, stiff, and lightweight structures (Wicks and Hutchinson, 2001; Chiras et al., 2002; Wadley, 2002, 2006; Valdevit et al., 2004, 2006; Wicks and Hutchinson, 2004; Kooistra et al., 2007) with properties that can be more easily predicted than random cellular materials, such as foams (Gibson and Ashby, 1997). One of the more mechanically efficient ordered cellular materials on a per weight basis is the truss. Recent efforts have focused on manufacturing trusses with micro-scale struts (Wadley et al., 2003; Jacobsen et al., 2007a,b; Jacobsen et al., 2008). The bending stiffness of such materials has been further improved by implementing ordered micro-scale trusses as the cores in sandwich panels (Wadley et al., 2003).

Adding thermal functionality to a micro-scale truss to yield a multifunctional material has been investigated using externally driven convection (Kim et al., 2004; Tian et al., 2004; Lu et al., 2005), but this requires an external power supply to drive fluid flow, which increases the mass and size of the overall system. Heat pipes, which use evaporation of a working fluid combined with capillary pressure driven fluid flow to yield effective thermal conductivities greater than solid copper for delimited heat flux and temperature regimes, require no external power supply (Reay and Kew, 2006). By creating a heat pipe in the form of a sandwich panel with an ordered micro-scale truss core, a material with lightweight, structural, and thermal functionalities requiring no external power supply is realizable.

Design of multifunctional materials necessarily entails the simultaneous optimization of multiple objectives. Since the relative values of each objective are only known a priori in specialized cases, multiobjective optimization is well-suited for multifunctional materials design (Coello and Christiansen, 2000; Collette and Siarry, 2004; Valdevit et al., 2008). The performance maps generated with multiobjective optimization can be used to judge the extents of feasibility and to aid in understanding the trade-offs between functionalities in the design process.

This work applies multiobjective optimization to the design of a multifunctional sandwich panel material. The material considered is a sandwich panel heat pipe with core consisting of a micro-scale truss for combined structural, lightweight, and thermal functionalities. The constitutive equations describing the material performance as a function of truss core structure are developed, the optimization algorithm is detailed, and various designs and different materials sets are compared.

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Nomenclature

A_{node}	cross-sectional node area (m^2)
a	micro-scale truss unit cell base length (m)
$\vec{a}$	material properties (various units)
b	node-to-node distance in the direction of flow (m)
d	diameter (m)
D_H	hydraulic diameter (m)
E	Young's modulus (Pa)
f_1	density objective function (kg/m^3)
f_2	compressive modulus objective function (Pa)
f_3	maximum heat flux objective function (W/m^2)
f_4	compressive strength objective function (Pa)
$\vec{g}$	equality constraints (various units)
h	aperture height (m)
$\vec{h}$	inequality constraints (various units)
H	total height (m)
K_{cell}	pressure loss coefficient
L	heat pipe length (m)
L_{evap}	evaporator length (m)
$\overrightarrow{LB}$	lower bounds (various units)
n	number
N	number of unit cells
Q	heat flux (W/m^2)
r	micro-scale truss strut radius (m)
R	ideal gas constant (J/mol K)
Re	Reynolds number
s	spacing (m)
S	strength (Pa)
t	thickness (m)
T	heat pipe operating temperature (K)
$\overrightarrow{UB}$	upper bounds (various units)
v	*average* velocity (m/s)
w	aperture width (m)
$\vec{x}$	dimensions to be optimized (various units)
y	solid volume fraction

Greek symbols

γ	specific heat ratio
ΔP	pressure difference (Pa)
ΔH_{vap}	heat of vaporization (kJ/kg)
ε	ratio of open area to total cross-sectional area normal to the flow direction
θ	angle between the face sheet and the diagonal truss members (rad)
μ	viscosity (kg/m s)
ρ	density (kg/m^3)
ρ_A	area density (kg/m^2)
σ	surface tension (N/m)
φ	contact angle (rad)
χ	open area ratio at the vapor–liquid interface

Subscripts

boiling	boiling limit
buckle	buckling failure
cap	capillary
core	core material
entrainment	entrainment limit
face	face sheet material
fluid	working fluid
G	gravitational
j	second objective index
k	third objective index
l	fourth objective index
L	liquid region
max	maximum
mesh	mesh
pore	pore
sonic	sonic limit
total	total
truss	truss
V	vapor region
w	wall
wicking	wicking limit
yield	yielding failure

2. Problem definition

2.1. Geometrical parameters

The design to be optimized is depicted in Fig. 1. The sandwich panel consists of two face sheets with a micro-scale truss core, which is subdivided into a region for vapor flow in the +*x* direction and an arterial wick for liquid flow in the $-x$ direction. A heat source is applied at the evaporator region and a heat sink is applied to the condenser region. The total length of the heat pipe, L, is 0.2 m, with the evaporator region length, L_{evap}, comprising 0.02 m of the overall heat pipe length. The heat pipe is considered to be operating in the isothermal regime. A mesh at the liquid–vapor interface separates the liquid and vapor regions and provides the pores necessary for capillary action and thus also heat pipe operation. This mesh intersects a coplanar set of nodes in the micro-scale truss core, thus demarking a vapor region of the core and a liquid region of the core. The periodic micro-scale truss core has D_{4h} group symmetry and consists of solid, cylindrical struts of diameter, d, oriented at an angle, θ, to the face sheets. Nodes are formed at intersections of four struts. The unit cell of the micro-scale truss core is depicted in Fig. 2a. Further details regarding the micro-scale truss are described elsewhere (Jacobsen et al., 2007a,b). Stainless steel 500 wire mesh with 30 μm openings, 20 μm wire diameter and 36% open area is used.

The dimensions that are varied during the optimization include the micro-scale truss unit cell base length, a, the angle between the face sheet and the diagonal truss members, θ, the micro-truss strut diameter, the number of unit cells comprising the height of the liquid region, N_L, the number of unit cells comprising the height of the vapor region, N_V, and the face sheet thickness, t_w. Upper and lower limits are imposed on each variable to limit the search space for the optimization and are given in Table 1. However, the only bounds found to limit the optimization are the minimum bound of one unit cell in the liquid region and the minimum bound on the face sheet thickness (see Appendix A Figs. A.1–A.3 for details and trends of optimized design variable values).

2.2. Objective equations

The objectives to be considered are the density, f_1, the compressive modulus, f_2, the maximum heat flux which can be tolerated before heat pipe failure, f_3, and the compressive strength, f_4. The flexural stiffness and strength, two additional objectives which are important in sandwich panel design, as well as the effective thermal conductivity of the heat pipe are not considered in this