International Journal of Heat and Mass Transfer 75 (2014) 58–74

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Rough surfaces with enhanced heat transfer for electronics cooling by direct metal laser sintering

Luigi Ventola [a], Francesco Robotti [a], Masoud Dialameh [a], Flaviana Calignano [b], Diego Manfredi [b], Eliodoro Chiavazzo [a], Pietro Asinari [a,*]

[a] Multi-Scale ModeLing Laboratory (SMaLL), Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

[b] Center for Space Human Robotics IIT@Polito, Istituto Italiano di Tecnologia, Corso Trento 21, 10129 Torino, Italy

ARTICLE INFO

Article history:
Received 16 August 2013
Received in revised form 11 March 2014
Accepted 11 March 2014

Keywords:
Heat transfer enhancement
Turbulent convective heat transfer
Electronics cooling
Artificial roughness
Selective Laser Melting
Direct metal laser sintering

ABSTRACT

Experimental evidences are reported on the potential of direct metal laser sintering (DMLS) in manufacturing flat and finned heat sinks with a remarkably enhanced convective heat transfer coefficient, taking advantage of artificial roughness in fully turbulent regime. To the best of our knowledge, this is the first study where artificial roughness by DMLS is investigated in terms of such thermal performances. On rough flat surfaces, we experience a peak of 73% for the convective heat transfer enhancement (63% on average) compared to smooth surfaces. On rough (single) finned surfaces, the best performance is found to be 40% (35% on average) compared to smooth finned surface. These results refer to setups with Reynolds numbers (based on heated edge) within $3500 \lesssim Re_L \lesssim 16,500$ (corresponding to $35,000 \lesssim Re_D \lesssim 165,000$ in terms of Reynolds number based on hydraulic diameter). Experimental data are obtained by a purposely developed sensor with maximum and mean estimated tolerance intervals of $\pm 7.0\%$ and $\pm 5.4\%$, respectively. Following the idea by Gioia et al. (2006) [48], we propose that heat transfer close to the wall is dominated by eddies with size depending on the roughness dimensions and the viscous (Kolmogórov) length scale. An excellent agreement between the experimental data and the proposed analytical model is finally demonstrated.

1. Introduction and motivation

Thermal management of the microprocessors used in notebook and desktop computers often relies on chip-attached or adhesively bonded extruded aluminum heat sinks, cooled by remotely located fans [1]. In particular, battery power limitations in notebook computers represent a motivation to keep searching for heat sinks with enhanced performances. Highly efficient heat sinks, with reduced thermal resistances, are required also by high-end commercial workstations and servers. Many details about the thermal management of electronic devices and practical issues associated with the efficient packaging are reported in Refs. [2,3]. Even though water-based two-phase cooling systems are known to ensure remarkably high heat fluxes (two- or three orders of magnitude higher than forced air systems), it is difficult to imagine a widespread use of such a technology in notebook computers, which will remain dominated by forced air convection cooling systems reasonably for long time. However, in the next-generation electronics devices, thermal performances of the air-cooled heat sinks must be further improved due to a steadily increasing power density, which makes the thermal management a great challenge still to be faced in the next future [4].

Forced air heat transfer enhancement has been extensively explored and many augmentation techniques have been already proposed [5], including plane fins [6,7], pin fins [8–10], dimpled surfaces [11–13], surfaces with arrays of protrusions [14,15], metal foams [16], and artificial surface roughness [17]. By *artificial surface roughness*, we mean any surface patterning with enough regularity and purposely designed in order to enhance heat transfer. For instance, in such a category, we may include ribs [18–20] and, more recently, (shark-skin-like) scale roughened surfaces [21,22]. The resulting heat transfer enhancement of the scale roughened surface is surprisingly good compared to rib roughened and dimpled surfaces [23]. This proves that there is still room for improving the optimal design of artificial surface roughness. To this respect, an interesting possibility consists in adopting a multi-scale strategy, where pin micro-fins are placed on standard plate fins. Recently, Authors in Ref. [24] showed that pin fins of five different cross-section shapes in channels of plate-fin heat sinks cause enhancement in the heat transfer. Short pin fins, on surfaces

* Corresponding author. Tel.: +39 0110904434; fax: +39 0110904499.
E-mail address: pietro.asinari@polito.it (P. Asinari).
URL: http://www.polito.it/small (P. Asinari).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.03.037
0017-9310/© 2014 The Authors. Published by Elsevier Ltd.

Nomenclature

A	flat surface area $[m^2]$
A_f	total effective surface area $[m^2]$
A_{ff}	finned surface area $[m^2]$
A_{fb}	base surface area $[m^2]$
D	hydraulic diameter [m]
E	heat transfer enhancement [–]
f	friction factor [–] or probability density function [1/m]
h	convective heat transfer coefficient $[W/m^2/K]$
h_f	average convective heat transfer coefficient for finned surface $[W/m^2/K]$
h_d	hatching distance [mm]
k	core-to-guard thermal transmittance [W/K] ; slicing direction [–]
k_a	average surface roughness w.r.t. fluid-dynamic plane [μm]
k_p	peak surface roughness w.r.t. fluid-dynamic plane [μm]
k_s	grain size diameter [μm]
k_0	tunable shifting parameter [μm]
L	heating edge [m]
l	fin length [mm]
m	wave number $[mm^{-1}]$
n	number of measurements [–]; direction normal to a sample face [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
p	pressure [Pa]
P	probability [–] ; laser power [W]
q	generic independent quantity, various units
R	hydraulic radius [μm]
R_h	heater electric resistance $[\Omega]$
R_a	average roughness [μm]
R_p	peak roughness [μm]
R_z	five-peak-valley roughness [μm]
rs_{angle}	angle between the rough surface and the building platform [degree]
S	surface $[m^2]$
S_a	average surface roughness [μm]
S_{ku}	kurtosis surface roughness [μm]
s	minimum distance between sample temperature probe and sample surface [mm]
S_p	peak surface roughness [μm]
S_q	root mean square surface roughness [μm]
S_{sk}	skewness surface roughness [μm]
Re	Reynolds number [–]
T	temperature [K]
t	fin thickness [mm]
V	potential difference [V]
v	fluid velocity [m/s]; scan speed [mm/s]
y_0	friction length [μm]
z	height w.r.t. fluid-dynamic plane [μm]
z_d	roughness displacement [μm]
z_0	aerodynamic roughness length [μm]

Greek symbols

α	significant level [–]
γ	energetic range of turbulence spectrum [–]
δ	size of the Kolmogórov smallest eddies [–]
ϵ	emissivity [–]
η	viscous length scale [μm]
η_A	aerothermal efficiency [–]
η_f	fin efficiency [–]
ϑ	angle between the normal to a sample face and the slicing direction [degree]
κ	Von Kármán's constant [-]
λ	thermal conductivity of air $[W/m/K]$
λ_s	thermal conductivity of sample $[W/m/K]$
λ_f	roughness frontal aspect ratio [–]
λ_p	roughness plan aspect ratio [–]
ν	kinematic viscosity $[m^2/s]$
ρ	density $[kg/m^3]$
σ	relative standard uncertainty [–]
Σ	standard uncertainty, various units
σ_B	Stefan–Boltzmann constant $[W/m^2/K^4]$
τ	shear stress $[N/m^2]$
ϕ	specific thermal flux $[W/m^2]$
ω	critical value of k_s^+ for viscous sublayer [–]

Subscripts and superscripts

a	air
A	type A uncertainty
AS	almost smooth
B	Blasius or type B uncertainty
d	downstream
eff	effective
D	hydraulic diameter
F	fitting
f	finned sample
ff	fin of the finned sample
fb	base of the finned sample
g	guard (sensor)
$g1$	upstream guard (sensor)
$g2$	downstream guard (sensor)
G	Gioia et al.
i	index of the ith independent quantity
L	heating edge
m	mean line/plane
N	Nikuradse
q_i	ith independent quantity
r	rough
s	sample (sensor)
sf	solid–fluid interface
u	upstream
w	wall
$+$	turbulence dimensionless quantities

of plate-fin heat sinks, prove to be particularly effective, in spite of their modest thicknesses: Authors in Ref. [25] achieved a heat transfer enhancement of 78% by pin fins shorter than 350 μm. These first results seem to open the field to a *hierarchical* design of micro-structures, purposely designed in order to exploit at best the thermo-fluid dynamics boundary layers and thus achieve the highest heat transfer coefficient. Another interesting possibility consists in using ionic wind engines, which can be integrated onto surfaces to provide enhanced local cooling [26]. Air ions generated by field-emitted electrons or corona discharges are pulled by an electric field and exchange momentum with neutral air molecules, causing air flow [26]. Beyond pin micro-fins, sharp electrodes by wires can also be adopted [27].

Micro-fins patterning of heat sinks made by standard milling for electronics cooling may be impracticable due to technological constraints (e.g. accessibility of fin surfaces in plate fins) and/or not economically viable (because it would require an additional post-processing in manufacturing). On the other hand, additive manufacturing (AM) technologies represent an interesting alternative. The ability to modify a design and to create immediately the component designed, without wasteful casting or drilling, makes additive manufacturing an economical way to fabricate single