Influence of porosity on the conductivity of selective laser melted stainless steel [1]

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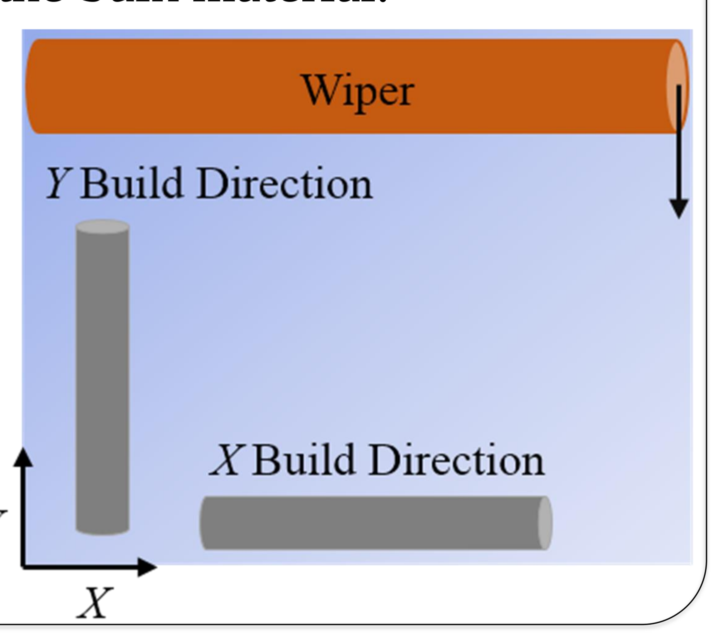
Introduction

- The thermal conductivity of a material may vary significantly from the nominal value; therefore, being able to estimate the thermal conductivity of a material becomes important for thermal applications.
- The approach to estimate thermal conductivity developed in [2] was applied to 1.4 to 7 % porosity selective laser melted stainless steel specimens.

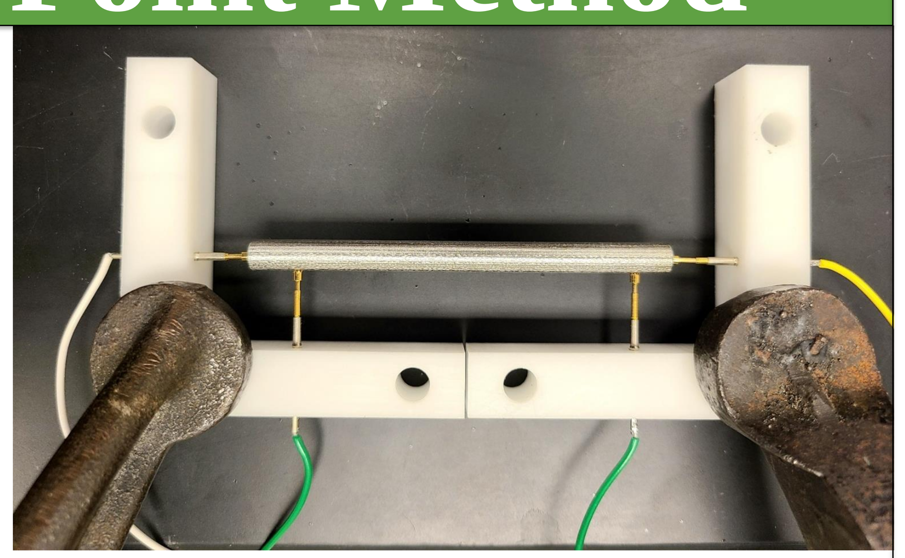
Background

- Additively manufactured (AM) parts are increasingly being used in thermal applications to reduce weight and increase performance [3,4].
- The quality of an AM part is highly dependent on the process parameters used and could cause unintended increased porosity in the final part.
- The change in porosity can cause the conductivity to vary significantly from the bulk material.
- Two build directions with two variants of process parameters (scan speed and hatch spacing) yielding four porosities were used to qualify the proposed method.



Four Point Method

- The electrical conductivity can be shown to be directly proportional to the thermal conductivity [5].



- The electrical conductivity results were used to corroborate the thermal conductivity results.
- The setup was performed following NIST 1531 [6].

$$\sigma = \frac{4L}{\pi d^2}\frac{1}{R_r}\frac{V_r}{V_m}$$

d	Rod diameter
L	Length between probes
R_r	Resistor resistance
V_m	Probe voltage
V_r	Resistor voltage
σ	Electrical conductivity

Thermal Conductivity Estimation

Governing equation [2,7]:

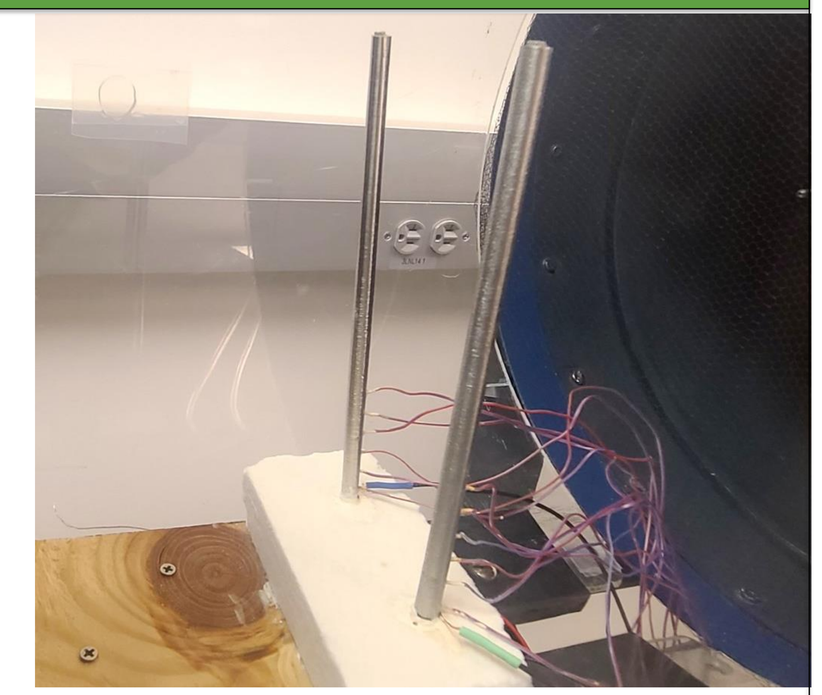
$$\frac{\partial\theta}{\partial t} = \kappa\frac{\partial^2\theta}{\partial x^2} - \nu\theta$$

where,

$$\kappa = \frac{k}{\rho c} \qquad \nu = \frac{hs}{\rho A c}$$

Boundary conditions:

$$\frac{\partial\theta}{\partial x}(0,t) = \frac{-P\left(1-e^{-\alpha(t+\tau)}\right)}{kA} \qquad \frac{\partial\theta}{\partial x}(L,t) = 0$$



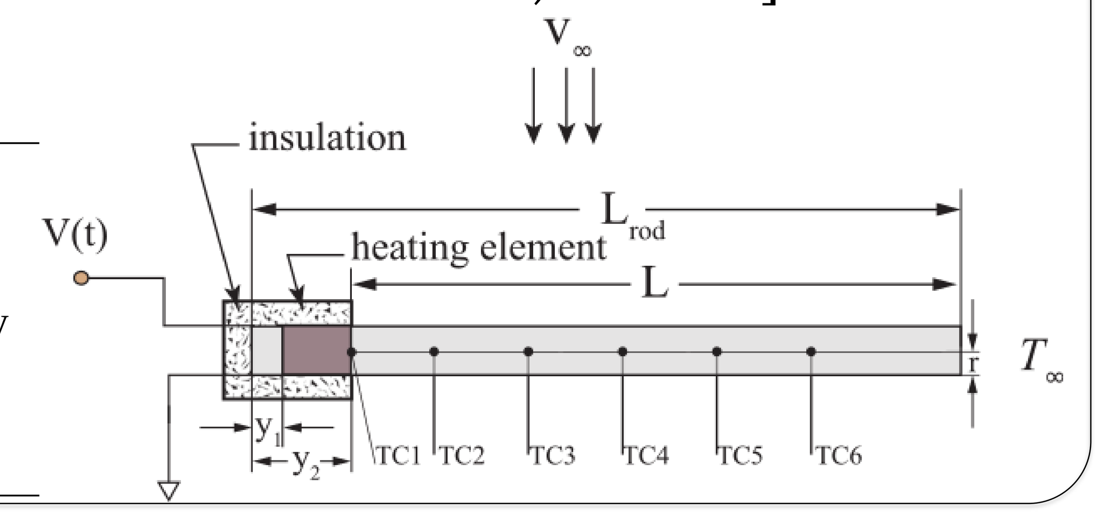
Solution to the governing equation:

$$T(x,t) = T_\infty + \frac{P\left(\nu e^{-\alpha\tau-\nu t} - \nu e^{-\alpha(t+\tau)} + (\nu-\alpha)(1-e^{-\nu t})\right)}{AcL\nu\rho(\nu-\alpha)} + \frac{2P}{AcL\rho}\sum_{n=1}^{\infty}\left[\left(\frac{e^{-(\beta_n^2+\nu)t-\alpha\tau} - e^{-\alpha(t+\tau)}}{\beta_n^2-\alpha+\nu} + \frac{1}{\beta_n^2+\nu} - \frac{(\beta_n^2-\alpha+\nu)e^{-(\beta_n^2+\nu)t}}{(\beta_n^2-\alpha+\nu)(\beta_n^2+\nu)}\right)\cos\frac{\beta_n}{\sqrt{\kappa}}x\right]$$

where,

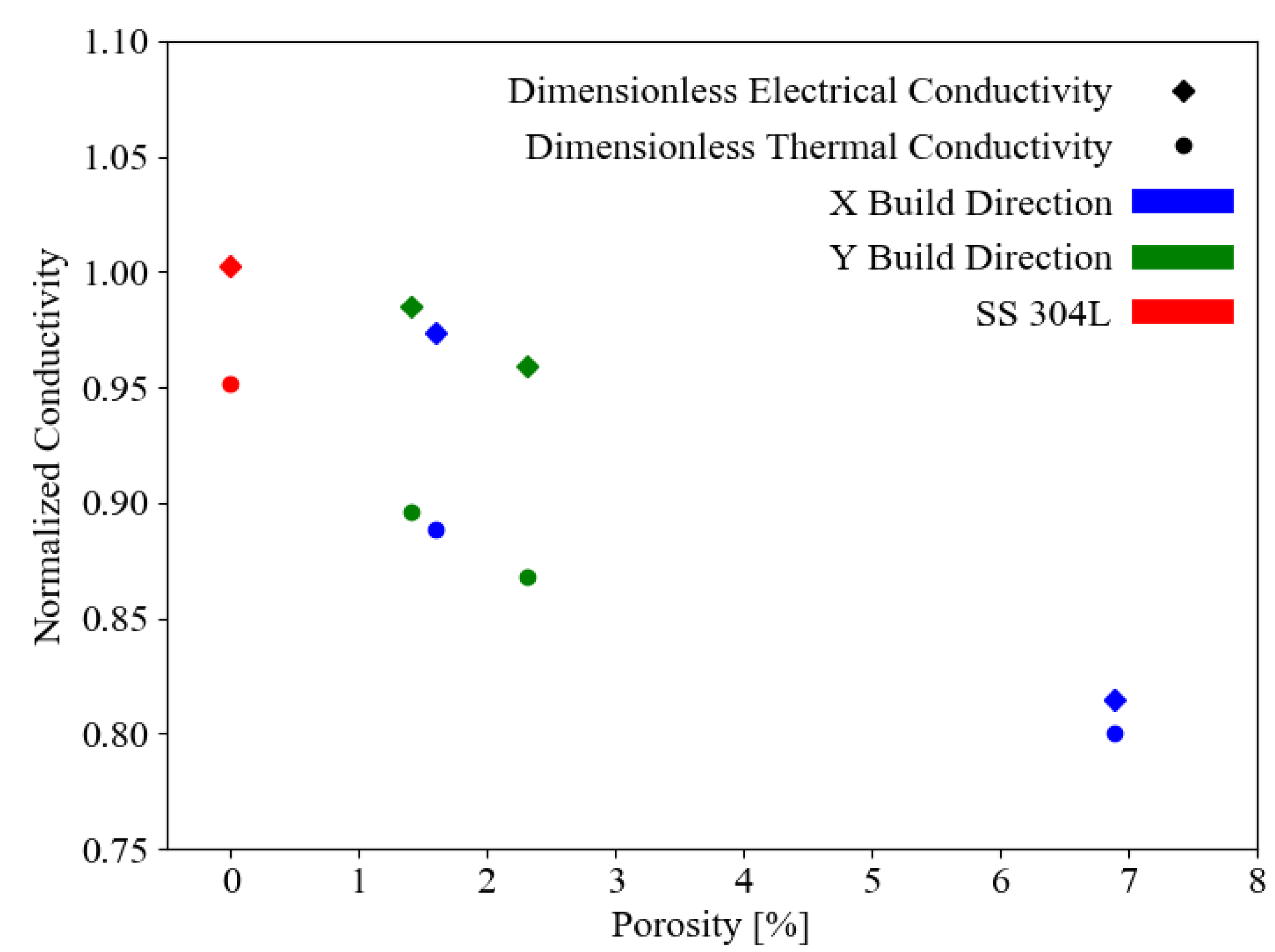
$$\beta_n = \frac{n\pi}{L}$$

A	Cross-sectional area	T	Temperature
c	Specific heat	T_∞	Ambient temperature
h	Heat transfer coefficient	x	Distance
L	Length of the rod	α	Heat flow into the boundary
P	Steady state power into the rod	ρ	Density
s	Perimeter	τ	Heating delay
t	Time		



Results

- The AM specimens were prepared and had a porosity range from 1.4 to 7 % porosity.
- The resulting measured porosity varied from the intended porosity due to build characteristics.
- The AM specimens were also compared to a wrought stainless steel specimen.
- The results show that the conductivity decreased with increased porosity.



Parameter	Units	SS 304L	$X_{1.60}$	$X_{6.90}$	$Y_{1.40}$	$Y_{2.31}$
Density	kg/m³	8030	7813 ± 209	7392 ± 149	7829 ± 206	7757 ± 202
Porosity	%	0	1.60 ± 0.20	6.90 ± 0.14	1.40 ± 0.20	2.31 ± 0.20
Thermal Conductivity	W/mK	15.42 ± 0.16	14.39 ± 0.09	12.97 ± 0.05	14.52 ± 0.06	14.06 ± 0.06
Electrical Conductivity	MS/m	1.392 ± 0.017	1.352 ± 0.014	1.132 ± 0.012	1.369 ± 0.015	1.332 ± 0.014

Conclusions

- The results demonstrated that thermal conductivity decreases with increasing porosity and was corroborated by a corresponding reduction in electrical conductivity.
- From the results, there is a dependency on process parameters used (build direction, scan speed, and hatch spacing) and overall performance of AM parts.
- The proposed method is sensitive enough to characterize small changes of porosity in AM parts.
- The method can be further applied to evaluate other materials.

Publications

[1] L. B. Tomanek, D. S. Stutts, T. Pan, F. Liou, "Influence of porosity on the thermal, electrical, and mechanical performance of selective laser melted stainless steel," Additive Manufacturing 39 (2021). doi:10.1016/j.addma.2021.101886.
[2] L. B. Tomanek, D. S. Stutts, "Material Thermal Properties Estimation Via a One-Dimensional Transient Convection Model," Applied Thermal Engineering 184 (2021). doi:10.1016/j.applthermaleng.2020.116362.

References

[3] Comparison of Louvered Plate-Fin Heat Exchangers Made via Additive Manufacturing, Vol. 2: Advanced Manufacturing of ASME International Mechanical Engineering Congress and Exposition. doi:10.1115/IMECE2018-87941
[4] Y. Cormier, P. Dupuis, B. Jodoin, A. Corbeil, Pyramidal fin arrays performance using streamwise anisotropic materials by cold spray additive manufacturing, J. Therm. Spray Technol. 25 (1–2) (2015) 170–182, doi:10.1007/s11666-015-0267-6.
[5] M.D. Janezic, R.F. Kaiser, J. Baker-Jarvis, G.M. Free, DC conductivity measurements of metals, Tech. rep., 2004. 10.6028/nist.tn.1531.
[6] J.C. Maxwell, A Treatise on Electricity and Magnetism, Clarendon, Oxford, 1881.
[7] H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids, Clarendon.