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Evaluation of a Low-Cost System for Measuring Thermal Conductivity in 3D-Printed Metallic Structures

Maria H. Friedo[1,a*], M.T. Hauschultz[1,b], H. Jacobs[1,c], C. Kallabis[1,d], M. Richetta[2,e], A. Böhme[1,f] and R. Krenz-Baath[1,g]

[1]Technical University of Applied Sciences Wildau, Hochschulring 1, 15745 Wildau, Germany

[2]Department of Industrial Engineering, University of Rome Tor Vergata, Via del Politecnico 1, 00133 Rome, Italy.

[a]maria_helene.friedo@th-wildau.de, [b]mike.hauschultz@th-wildau.de, [c]jacobs@th-wildau.de, [d]conrad.kallabis@th-wildau.de, [e]richetta@uniroma2.it, [f]aboehme@th-wildau.de, [g]rene.krenz-baath@th-wildau.de

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Abstract. Novel injection moulding tools have been developed using metal additive manufacturing, particularly Selective Laser Melting (SLM). This technique enables the fabrication of new complex geometries, including the integration of lattice structures within components. These structures are renowned for their lightweight and high-strength characteristics. When designed with enhanced thermal properties, lattice structures have the potential to significantly improve the performance of injection moulding tools, where efficient thermal management is of importance.

To realise these innovative thermal capabilities, a comprehensive investigation of the thermal behaviour and conductivity of the structures is essential.

To this end, a cost-effective experimental setup has been designed and constructed. The system employs a comparative method, whereby heat flow through a 3D-printed sample is measured in series with a reference material. By analysing the temperature gradients across both bodies, the thermal conductivity of the printed structure can be accurately determined. BK7 glass is utilised as the reference material because of its well-characterised and stable thermal conductivity.

A key factor affecting measurement accuracy is interfacial thermal resistance, which arises at the contact interface between two materials and can hinder heat transfer. This resistance is influenced by the material properties, surface finish and contact pressure. To minimize the effect of interfacial resistance and ensure more reliable conductivity measurements, multiple tests are conducted on the same structure under varying temperature conditions. This approach facilitates the identification and compensation of thermal contact resistances.

Introduction

Effective temperature regulation in injection moulding tools is critical for ensuring both production efficiency and product quality. Lightweight structures produced via Selective Laser Melting (SLM) offer significant potential for improving thermal management, owing to their design flexibility and tailored properties. However, accurately determining the thermal conductivity of such metallic lattice structures remains a considerable challenge due to their geometric complexity and material inhomogeneity [1]. These characteristics often necessitate larger specimens to achieve reliable measurements. At the same time, the need for frequent design iterations calls for an accessible and cost-effective method to compare the thermal performance of different geometries.

The complexity arises from both the structural and material aspects of additively manufactured lattices. Internally, they often exhibit porosity, unmolten powder particles, and microstructural inhomogeneities. Geometrically, their thin struts, curved surfaces, and open-cell architectures introduce complex, anisotropic heat transfer pathways. Conventional methods developed for homogeneous or bulk materials are frequently unsuitable or yield unreliable results when applied to such structures [2].

To address these challenges, this study introduces a practical and cost-efficient measurement system specifically designed to evaluate the thermal conductivity of 3D-printed metallic lattice structures. The system aims to provide consistent and reproducible results, while maintaining accessibility for standard laboratory environments.

State of the Art. Accurate measurement of thermal conductivity is essential for optimizing thermally functional components. However, standard methods are often inadequate for complex geometries inherent to additive manufacturing (AM) [3].

SLM enables the production of metallic lattice structures with lightweight and customisable thermal properties. Nonetheless, their intricate geometry, thin struts, and high surface-to-volume ratios, combined with manufacturing defects such as porosity and anisotropic microstructures, substantially affect heat transfer. These features result in significant deviations from bulk thermal conductivity values, thereby limiting the applicability of conventional measurement techniques [1].

Recent efforts have explored numerical simulations, inverse modelling, and custom-built experimental setups.

Several low-cost solutions have emerged based on simplified heat flux techniques or the use of affordable sensors. For instance, Sarap [4] proposed an experimental approach for determining the thermal conductivity of AM parts, while Sparavigna [5] introduced a basic setup using thermocouples and numerical models for educational purposes. While these approaches are economical, they often lack robustness, particularly when managing heat losses, high temperatures or complex geometries, like lattice structures.

Comparative methods employing reference materials, where thermal conductivity is inferred from temperature gradients across known and unknown specimens, offer improved precision and systematic error control. However, applying such techniques to lattice structures remains challenging due to anisotropy and boundary effects, necessitating custom configurations and precise thermal control.

A promising development involves sandwich-like measurement setups that incorporate sensors or reference bodies. These configurations enhance adaptability for open-cell structures but still face challenges related to reproducibility and scalability. Effective thermal isolation is crucial in minimizing measurement errors. In this regard, polytetrafluoroethylene (PTFE, or Teflon) has proven effective, offering a combination of low thermal conductivity, mechanical stability and machinability [6].

Recent advancements have improved the accuracy of low-cost thermal conductivity measurement systems through the integration of advanced sensors and materials. Micro-sensor integration, highlighted in recent studies published in *Sensors* [3, 7], has increased precision under elevated temperature conditions.

Despite these developments, there remains a clear need for a robust, adaptable, and economically feasible methodology for evaluating thermal conductivity in complex SLM-manufactured lattice structures. This work addresses that need by presenting and validating a simplified, low-cost test stand capable of producing reproducible thermal conductivity measurements. The design emphasises high-temperature compatibility and incorporates materials such as PTFE for effective thermal isolation. Future research will expand upon this proof of concept, focusing on error mitigation, scalability, and adaptability to various SLM-manufactured geometries.

Methodology

To overcome the limitations of conventional approaches and enable accurate measurement of the thermal conductivity of 3D-printed lattice structures, a low-cost, in-house measurement system was developed. This system is specifically tailored to accommodate complex lattice geometries. The methodology is based on a comparative approach using BK7 optical glass as a reference material, due to its well-established thermal conductivity [7, 8]

Experimental Setup. The test specimen and reference material are arranged in series between a heat source and a heat sink, ensuring identical thermal boundary conditions. Temperatures are monitored at three critical points: the heat source (T_1), the interface between the sample and reference material (T_2) and the heat sink (T_3) (see Figure 1). Figure 1 also highlights the measures taken to ensure accuracy: BK7 glass provides a reliable reference, Teflon blocks reduce lateral heat losses, and the spring system guarantees constant contact pressure at the interfaces. Once thermal equilibrium is reached, the thermal conductivity (λ) of the test specimen is computed.

The setup comprises several key components designed to maintain stable and accurate thermal conditions. On the hot side, cartridge heaters embedded in a copper block deliver a constant and controllable heat input. On the cold side, a Peltier element enables active cooling and precise temperature regulation. Temperature measurements are conducted using PT1000 strategically positioned within the system. An Arduino-based microcontroller governs the heating and cooling elements, collects temperature and force sensor data, and continuously logs measurement results. Teflon insulation blocks enclose the thermal path, effectively minimising lateral heat losses. To ensure consistent mechanical contact at the interfaces, a spring system coupled with an FSR400 force sensor is used.

Measurements. Uniform lattice specimens based on a body-centred cubic (BCC) geometry were fabricated using stainless steel 316L (1.4404), a material widely adopted in metal additive manufacturing for its favourable mechanical and thermal properties. Each specimen features a cross-sectional width and length of 40 mm. To promote consistent heat transfer and uniform thermal contact, 2 mm thick solid end plates are added to both ends of each specimen. Thermal conductivity measurements were performed at three temperature levels: 120, 160 and 200 °C.

Determining System Resistance. Thermal conductivity, analogous to electrical conductivity, defines the ability of a material to conduct heat in response to a temperature gradient, with the heat flow proportional to the temperature difference and inversely proportional to the thermal resistance [9].

To compute the thermal conductivity of the lattice specimen, the overall thermal resistance of the system must first be established. This was achieved by performing a reference measurement with air in place of the test specimen. From this, the resistance contribution of the Teflon insulation (R_{Teflon}) was extracted. The total system resistance includes the resistance of air (R_{Air}), the known resistance of the BK7 glass reference material (R_{BK7}), and the insulation resistance (R_{Teflon}), all of which were incorporated into the final analysis of the lattice structures.

Thermal paste was applied in ultra-thin layers at the interfaces to minimize contact resistance. Given its high thermal conductivity and very small thickness, its contribution to the total resistance was negligible and therefore omitted from the calculations, consistent with established findings in the literature [10, 11]. (Eq. 1):

$$L_{Paste} \ll L_{Air}, L_{BK4}, L_{Teflon} \qquad \Rightarrow R_{Paste} \approx 0 \tag{1}$$

The total system resistance is determined using the temperature ratios and known values. From (Eq. 2):

$$\Delta T_1/\Delta T_2 = ((R_{Air}*R_{Teflon})/(R_{Air}+R_{Teflon}))*((R_{BK4}+R_{Teflon})/(R_{BK4}*R_{Teflon})) \tag{2}$$

The thermal resistance of the PTFE insulation (R_{Teflon}) is isolated and calculated. This value is then used in subsequent tests to extract the thermal resistance of the lattice (Eq. 3):

$$R_{Lattice} = (R_{Teflon}*R_{BK4}*\Delta T_1)/((R_{BK4}+R_{Teflon})*\Delta T_2-R_{BK4}*\Delta T_1) \tag{3}$$

Finally, the thermal conductivity λ of the Lattice structure is calculated through (Eq. 4)

$$\lambda_{Lattice} = L/(R_{Lattice}*A) \tag{4}$$

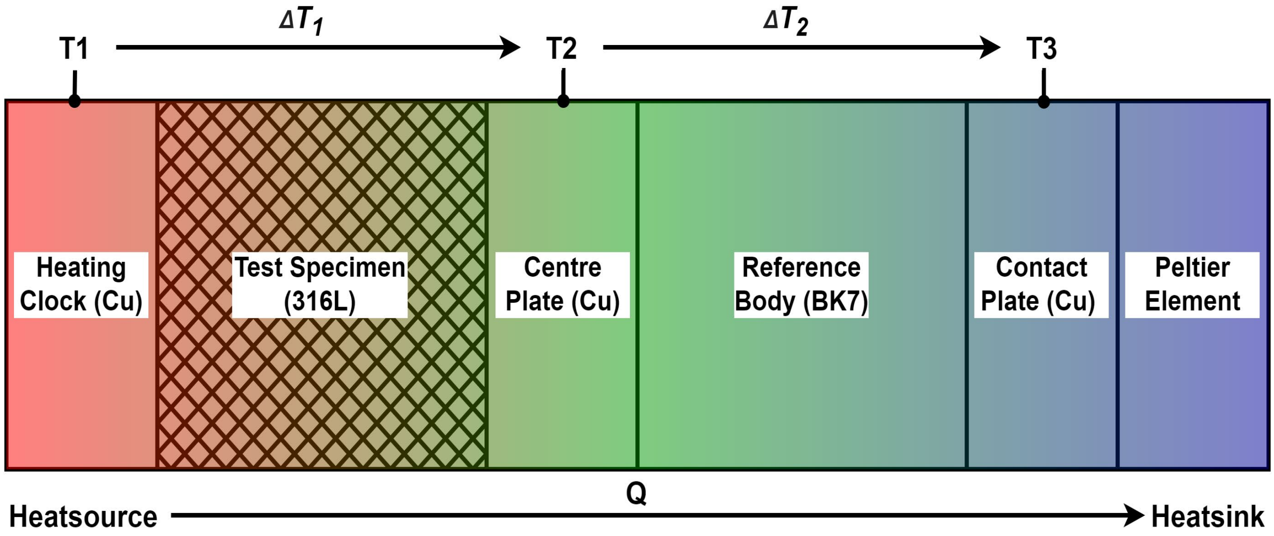

Fig.1. Schematic diagram of the experimental setup used to measure thermal conductivity. Heat flows from the heat source (left) to the heatsink (right) through a layered assembly. The test specimen (316L stainless steel) is placed between a heating block (Cu) and a centre plate (Cu). A reference body (BK7 glass) and contact plate (Cu) follow in sequence, with a Peltier element acting as the heatsink. Temperatures T1, T2, and T3 are measured at defined interfaces to calculate temperature gradients ΔT_1 and ΔT_2, enabling determination of the heat flux (Q).

Results and Discussion

This section presents a subset of the experimental results. To verify the reproducibility of the measurement system, three repeated tests using specimens with a fixed length of 40 mm and a heat source temperature of 120 °C (see Figure 2). In each test, the temperature at the centre plate (T_2) was recorded. The resulting temperature profiles show a high degree of overlap across all repetitions, as shown in Figure 2, the strong overlap of repeated runs and the high correlation of the exponential fit confirm the excellent reproducibility and stability of the setup.

Each test run lasted approximately 30,000 seconds (about 8.3 hours). To facilitate data interpretation and reduce noise, an exponential fitting function was applied to the measured temperature curves. The fitted curves show excellent agreement with the raw data, exhibiting a high correlation and confirming the suitability of the fitting method for further analysis (Figure 2: **Temperature measurements (T2) over time for three experiments at a boundary temperature of 120 °C and sample length of 40 mm. Blue lines represent measured data; red lines show exponential fits with high correlation (R = 0.989–0.991).**

To minimise potential assembly errors, particularly those arising when changing specimen lengths, final testing was performed exclusively with 40 mm-long specimens. Figure 3 presents three repeated measurement runs at each of the three heat source temperatures: 120 °C, 160 °C, and 200 °C. As expected, increasing the source temperatures leads to more rapid heating and higher steady-state temperatures at T_2. Once again, the close alignment of the curves across repetitions as shown in Figure 3, higher source temperatures accelerate heating and raise steady-state values, while the similarity of the curves across runs underscores the robustness of the measurement system..

Figure 4 displays the thermal conductivity values of the lattice structure calculated at the three temperature levels, based on the equations previously described. The results remain relatively stable, averaging slightly above 0.2 W/m·K. Owing to the high porosity and thin strut geometry of the lattice, the effective thermal conductivity is significantly reduced compared to bulk material, but it remains within the expected range for porous metal structures (typically 0.2–1.0 W/m·K) [12].

These findings validate the reliability of the proposed measurement method. The observed values are consistent with theoretical expectations: pure air exhibits a thermal conductivity of approximately 0.026 W/m·K, whereas solid 316L stainless steel typically ranges between 14 and 16 W/m·K. The measured values lie well within this interval, as anticipated for highly porous metallic lattices. This outcome confirms that the experimental setup accurately captures the effective thermal behaviour of porous metallic components and is thus well-suited for their thermal characterisation.

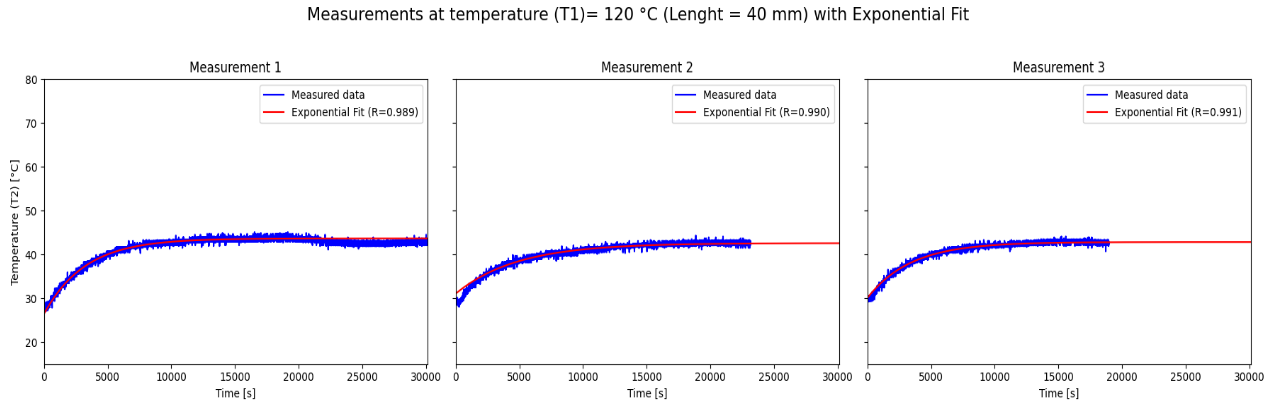

Fig. 2. Temperature measurements (T2) over time for three experiments at a boundary temperature of 120 °C and sample length of 40 mm. Blue lines represent measured data; red lines show exponential fits with high correlation (R = 0.989–0.991).

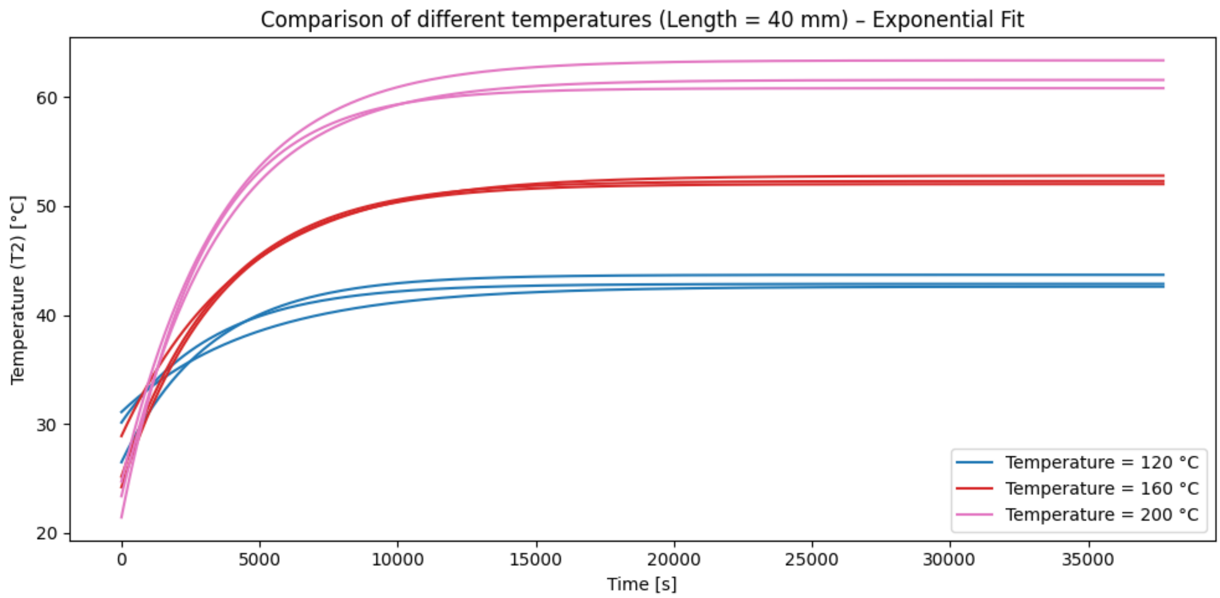

Fig. 3. Comparison of temperature measurements (T2) (exponential fit) at different heat source temperatures (120 °C, 160 °C, and 200 °C) for a constant sample length of 40 mm.

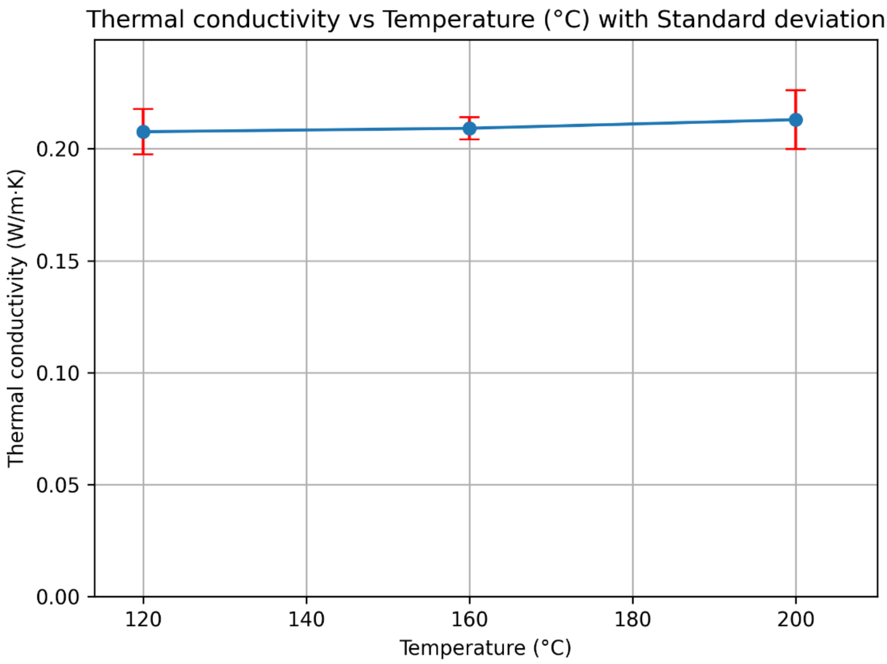

Fig. 4. Calculated thermal conductivity of the BCC lattice structure made from 316L stainless steel as a function of temperature. The experiments were conducted at 120 °C, 160 °C, and 200 °C. Error bars represent the standard deviation from multiple measurements.

Conclusion

A functional and cost-effective setup for determining the thermal resistance of 3D-printed lattice structures was developed and implemented. With a material cost of ~€300, the system offers an accessible solution for small laboratories and research institutions to characterise thermophysical properties of porous metallic components.

Experimental trials revealed limitations, including thermal losses from convection and radiation, heat conduction through insulation, and long times to reach steady state. To mitigate extended testing, exponential curve fitting was applied to transient temperature data, enabling efficient and accurate estimation of steady-state conditions.

The measurements produced consistent thermal conductivity values within the expected range for porous metallic lattices, confirming the system's ability to generate reliable, repeatable data and validating its suitability for thermal characterisation of additively manufactured components.

Future work will include additional lattice geometries to explore the link between material-to-air ratio and thermal performance, contributing to a deeper understanding of heat transfer in architected materials produced by Selective Laser Melting.

References

[1] Du Plessis, A., Razavi, N., Benedetti, M., Murchio, S., Leary, M., Watson, M., Bhate, D., and Berto, F. 2022. Properties and applications of additively manufactured metallic cellular materials: A review. *Progress in Materials Science* 125, 100918.

[2] Küster, W., Bode, K.-H., and Fritz, W. 1968. Beitrag zur Messung der Wärmeleitfähigkeit von Metallen im Bereich von 0 bis 500°C. *Wärme- und Stoffübertragung* 1, 3, 129–139.

[3] Zhao, D., Qian, X., Gu, X., Jajja, S. A., and Yang, R. 2016. Measurement Techniques for Thermal Conductivity and Interfacial Thermal Conductance of Bulk and Thin Film Materials. *Journal of Electronic Packaging* 138, 4.

[4] Sarap, M., Kallaste, A., Ghahfarokhi, P. S., Tiismus, H., and Vaimann, T. 2022. Determining the Thermal Conductivity of Additively Manufactured Metal Specimens. In *2022 29th International Workshop on Electric Drives: Advances in Power Electronics for Electric Drives (IWED)*. IEEE, 1–4. DOI=10.1109/IWED54598.2022.9722591.

[5] Sparavigna, A. C. 2012. Measuring the Thermal Diffusivity in a Student Laboratory. *ENG* 04, 05, 266–271.

[6] Price, D. M. and Jarratt, M. 2002. Thermal conductivity of PTFE and PTFE composites. *Thermochimica Acta* 392-393, 231–236.

[7] Janek, M., Kudelcik, J., Hardon, S., and Gutten, M. 2024. Novel, Cost Effective, and Reliable Method for Thermal Conductivity Measurement. *Sensors (Basel, Switzerland)* 24, 22.

[8] Antoniadis, K. D., Tyrou, A., Assael, M. J., Li, X., Wu, J., and Ebert, H.-P. 2020. Reference Correlations for the Thermal Conductivity of Solid BK7, PMMA, Pyrex 7740, Pyroceram 9606 and SS304. *Int J Thermophys* 41, 7.

[9] Guo, Z.-Y., Zhu, H.-Y., and Liang, X.-G. 2007. Entransy—A physical quantity describing heat transfer ability. *International Journal of Heat and Mass Transfer* 50, 13-14, 2545–2556.

[10] Cheung, S., Kang, J., Lin, Y., Goodson, K. E., Asheghi, M., and Gu, X. W. 2025. Triply periodic minimal surfaces for thermo-mechanical protection. *Scientific reports* 15, 1, 1688.

[11] Park, K., Kim, S., and Kim, J. 2024. Forced convection heat transfer in AlSi7Mg lattice structures fabricated by additive manufacturing. *Case Studies in Thermal Engineering* 61, 105006.

[12] Moustafa, A.R., Dinwiddie, R.B., Pawlowski, A.E., Splitter, D.A., Shyam, A., and Cordero, Z.C. 2018. Mesostructure and porosity effects on the thermal conductivity of additively manufactured interpenetrating phase composites. *Additive Manufacturing* 22, 223–229.

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