http://doi.org/10.35784/iapgos.6289

received: 17.07.2024 | revised: 23.08.2024 | accepted: 04.09.2024 | available online: 30.09.2024

THEORETICAL APPROACH FOR DETERMINING AN EMISSIVITY OF SOLID MATERIALS AND ITS COMPARISON WITH EXPERIMENTAL STUDIES ON THE EXAMPLE OF 316L POWDER STEEL

Oleksandr Vasilevskyi, Michael Cullinan, Jared Allison
The University of Texas at Austin, Walker Department of Mechanical Engineering, Austin, United States of America

Abstract. *The work used Maxwell's electromagnetic theory to quantitatively describe the emissivity of solid materials through electrical resistivity and temperature. An equation is proposed for recalculating the emissivity of smooth surfaces into powdery or rough surfaces. The obtained theoretical characteristics of the change in the emissivity of 316L powder steel were compared with experimental ones. As a result of the comparison, it was established that the experimental results obtained correlate with theoretical calculations and do not go beyond the limits of the expanded uncertainty of measurement.*

Keywords: additive manufacturing, the emissivity of the smooth surface, Maxwell's electromagnetic theory, the emissivity of the rough surface, 316L powder steel, machine learning

TEORETYCZNE PODEJŚCIE DO OKREŚLANIA EMISYJNOŚCI MATERIAŁÓW STAŁYCH I JEJ PORÓWNANIE Z BADANIAMI EKSPERYMENTALNYMI NA PRZYKŁADZIE STALI PROSZKOWEJ 316L

Streszczenie. *W pracy wykorzystano teorię elektromagnetyczną Maxwella do ilościowego opisania emisyjności materiałów stałych poprzez oporność elektryczną i temperaturę. Zaproponowano równanie umożliwiające przeliczenie emisyjności gładkich powierzchni na sypkie lub szorstkie powierzchnie. Uzyskane teoretyczne charakterystyki zmiany emisyjności stali proszkowej 316L porównano z doświadczalnymi. W wyniku porównania ustalono, że wyniki eksperymentalne uzyskały korelację z obliczeniami teoretycznymi i nie wykraczają poza granice rozszerzonej niepewności pomiaru.*

Słowa kluczowe: produkcja addytywna, emisyjność gładkiej powierzchni, teoria elektromagnetyczna Maxwella, emisyjność chropowatej powierzchni, stal proszkowa 316L, uczenie maszynowe

Introduction

In additive manufacturing of metals, non-contact temperature measurement methods based on the emissivity properties of materials are widely used today. For accurate temperature determination of materials used in additive manufacturing, it is necessary to know their emissivity characteristics over a wide temperature range in the visible and infrared areas of the spectrum. The need for such data is particularly strong due to the trend towards the intensification of thermal processes by increasing operating temperatures [3, 8, 12, 16–19, 21].

Theoretical determination of the emissivity characteristics of solid substances has received considerable attention, especially in works [8, 12, 16–18, 21]. These works extensively examine the conclusions obtained using electromagnetic (classical), electronic, and quantum theories. We will briefly consider these conclusions. The main goal of this article is to compare the obtained experimental data on determining the emissivity of 316L powder steel with existing theoretical methods for calculating the emissivity to test the hypothesis about the possibility of using them in machine learning algorithms.

1. Methods

The first attempts to compute emissivity characteristics were made within the framework of Maxwell's electromagnetic theory. According to this theory, the following relationship exists between the dielectric constant of the substance χ, its conductivity σ, and the frequency of the electromagnetic radiation υ incident on the substance.

$$\begin{cases} \chi = n^2 - k^2 \\ \sigma = nk\upsilon \end{cases} \tag{1}$$

where n is the refractive index; $k = \frac{m\lambda}{4\pi}$ is the absorption index; m is the absorption coefficient; λ is the wavelength of the incident radiation [8, 16–18].

The optical indices n and k depend on the wavelength λ and temperature T. These formulas are valid for isotropic materials with a magnetic permeability of $\mu=1$. If an electromagnetic wave is incident from a vacuum onto a metal with an optically smooth surface, then the reflectance at normal incidence will be equal to [16]

$$\rho_\lambda = \frac{(n-1)^2+k^2}{(n+1)^2+k^2} \tag{2}$$

The refractive index of metals can be expressed in complex form as $N = n - i^*k$, where $I = \sqrt{-1}$. Then the reflectance for normal incidence will be expressed as

$$\rho_\lambda = \left|\frac{N-1}{N+1}\right|^2 \tag{3}$$

It should be noted that the absorption index k in the metal, as well as in a dielectric, determines the attenuation of light waves. In the thickness of the metal, only a small part of the energy of the incident wave is converted into Joule heat. In the long-wavelength part of the radiation spectrum for metals $\sigma/\upsilon >> \chi$ [8, 16–18], and one can consider

$$n = k = \left(\frac{\sigma}{\upsilon}\right)^{0.5} \tag{4}$$

Then, using formula (1), for the reflectance, we obtain a series with terms decreasing in magnitude

$$\rho_\lambda = 1 - \frac{2}{n} + \frac{1}{n^3} + \cdots \tag{5}$$

Following Kirchhoff's law, monochromatic emissivity ε_λ equals monochromatic absorptivity a_λ or

$$\varepsilon_\lambda = a_\lambda = 1 - \rho_\lambda \tag{6}$$

since the transmittance is practically always zero [2, 4, 5].

Restricting ourselves to the first two terms in (5) and using formulas (4) and (6), we obtain

$$\varepsilon_\lambda = 2\left(\frac{\upsilon}{\sigma}\right)^{0.5} \tag{7}$$

Typically, the dependence for the emissivity ε_λ is represented as a function of wavelength λ and specific electrical resistance r_0 [6, 7, 9–11, 20]. Then formula (2) transforms into the following formula

$$\varepsilon_\lambda = 0.365\left(\frac{r_0}{\lambda}\right)^{0.5} \tag{8}$$

By the definition, the integral emissivity ε_i is described by the expression

$$\varepsilon_i = \frac{\int_0^\infty \varepsilon_\lambda I_\lambda d\lambda}{\int_0^\infty I_\lambda d\lambda} \tag{9}$$

where I_λ is the intensity of monochromatic radiation of a blackbody in the direction of the normal, which is calculated using Planck's formula [7, 12, 16].

If we use formula (9) and formulas (2) and (8), then for the integral normal emissivity ε_i we obtain the well-known Ashkinass relation

$$\varepsilon_i = 5.76(r_0 T)^{0.5} \tag{10}$$

where r_0 is the electrical resistivity of the material (Om·m), T is the temperature in Kelvin (K) [10, 11].

A formula that more accurately describes the dependence of the integral emissive power of metals on temperature and specific electrical resistance into which additional terms were introduced and numerical values of the coefficients were adjusted considering the radiation constants c_1 and c_2 [7, 10], is as follows

$$\varepsilon_i = 5.78(r_0 T)^{0.5} - 17.9 r_0 T + 44(r_0 T)^{1.5} \tag{11}$$

Formulas that reflect the dependence of emissivity power on the direction of radiation are derived based on Fresnel's formulas for reflection coefficients. Davisson and Weeks were the first to draw attention to the need to consider the dependence of the reflectivity of metals on direction [10, 16]. Considering the radiation constants c_1 and c_2, the Davisson and Weeks formula is written as follows

$$\varepsilon_{ih} = 7.54(r_0 T)^{0.5} - 63.5 r_0 T + 673(r_0 T)^{1.5} \tag{12}$$

It should be noted that the specified equations (10), (11), and (12) for calculating the emissivity of solid substances can only be applied to smooth surfaces.

It is also known from works [2, 4, 5] that the values of the emissivity of smooth solid metal surfaces can be converted into the values of the emissivity of the rough surface or metal powder. It is known that the emissivity increases with increasing surface roughness. If the roughness exceeds the radiation wavelength by several times, then the emissivity of the rough surface or metal powder ε_p can be recalculated using the following empirical formula

$$\varepsilon_p = \varepsilon_i(1+2.8[1 - \varepsilon_i]^2) \tag{13}$$

where ε_i is the emissivity of the smooth surface, ε_p is the emissivity of metal powder or the rough surface.

Thus, knowing the electrical resistivity and temperature of the metal using formulas (10)–(12), you can calculate the emissivity of a metal solid surface, after which, by substituting the emissivity values in formula (13), you can calculate the emissivity for the metal powder.

2. Results

To verify the theoretical information presented above regarding the possibility of calculating the emissivity of metals based on their specific electrical resistance and temperature, we conducted experimental studies to determine the temperature and emissivity of 316L powder steel. During the experiment, the 316L powder steel was heated to reference temperature values in the range from 333 K to 1174 K, which were determined using thermocouples and IR camera. The image of the experimental setup is shown in Fig. 1.

As a result of repeated studies to determine the emissivity of 316L powder steel, a characteristic of changes in the average values of the emissivity of metal powder as a function of temperature was obtained, which is presented in Fig. 2.

The relative value of the combined measurement uncertainty of the emissivity of 316L powder steel was 5.5% in the temperature range from 333 to 1174 K. In this case, the expanded uncertainty in determining the emissivity was ±0.06. Expanded measurement uncertainty shows the maximum possible deviations from the obtained average measurement result at each study point. This means that there is not one specific value for the measurement result, but rather many values within this range [13–15].

Since the resistivity values of metals are well known from reference data, for example, for stainless steel 316L its value is $7.4 \cdot 10^{-7}$ Ohm·m [1], then using equations (10), (11) it is possible to plot the dependence of the emissivity from temperature. Using formulas (10)–(12), which describe the dependence of emissivity on temperature at a known value of the resistivity of 316L powder steel, their variation characteristics were obtained in the Maple software (Fig. 3).

To construct theoretical dependences of the emissivity of 316L powder steel (the rough surface) on temperature, equation (13) was used, and their change characteristics were obtained, which are shown in Fig. 4. At the same time, the obtained experimental data on the emissivity of 316L powder steel, which are presented in Fig. 2, were also plotted in Fig. 4.

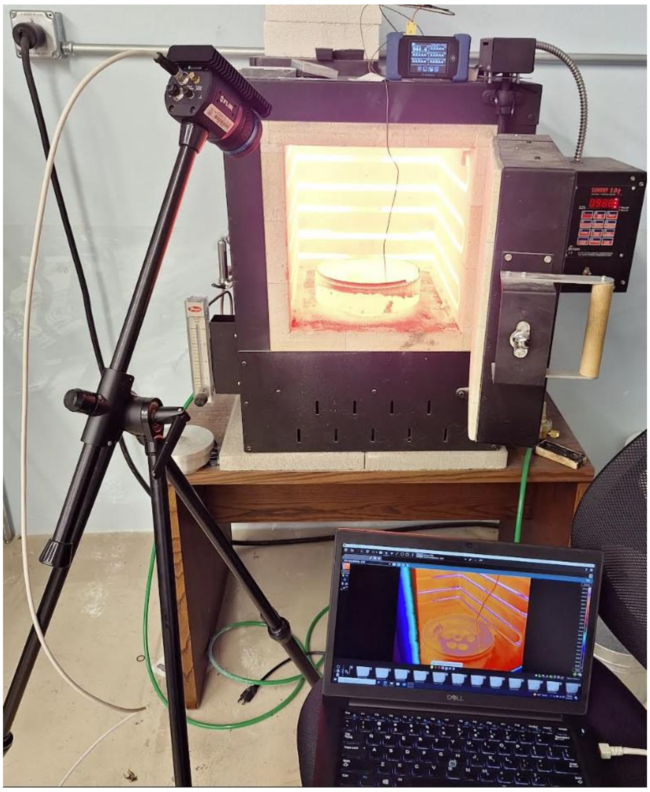


Fig. 1. Equipment for experimental determination of the emissivity of 316L powder steel in the temperature range from 333 K to 1174 K

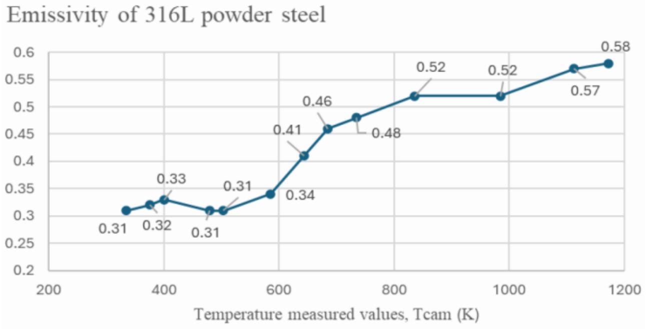


Fig. 2. Emissivity values for 316L powder steel in the temperature range from 333 K to 1174 K

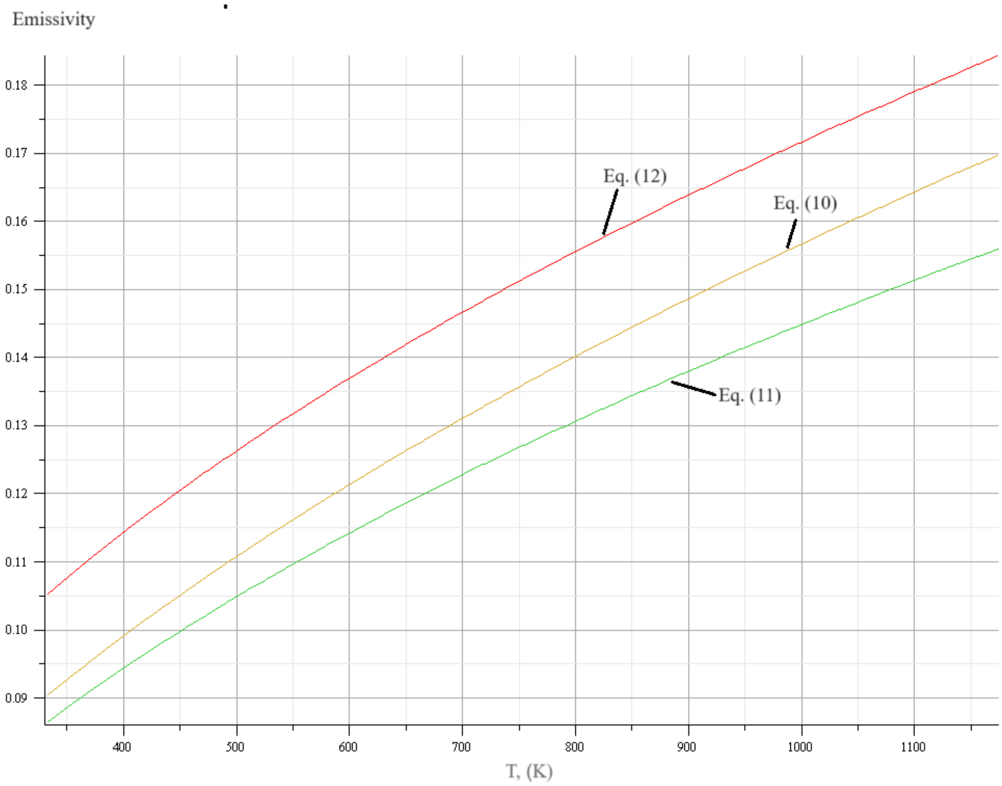


Fig. 3. Theoretical dependences of the emissivity of the solid smooth surface of 316L stainless steel on temperature in the range from 333 K to 1174 K

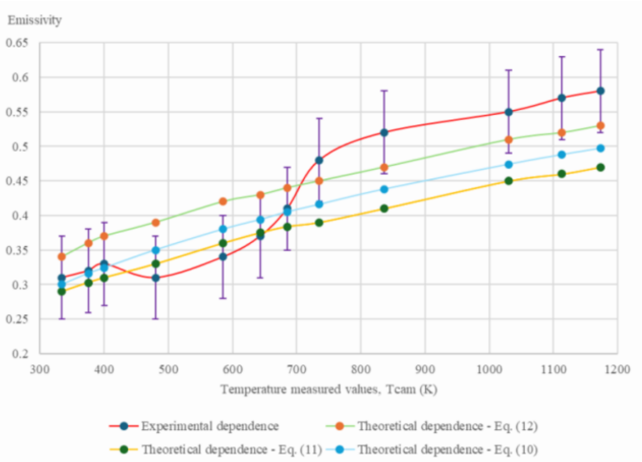


Fig. 4. Theoretical and experimental dependencies of the emissivity of 316L powder steel in the temperature range from 333 K to 1174 K

In Figure 4, the red line shows the experimental dependence of emissivity on temperature. The green line shows the theoretical dependence of emissivity on temperature, which is described by equation (12) after recalculating it according to equation (13) for non-smooth surfaces (metal powder). The blue line shows the theoretical dependence of emissivity on temperature, which is described by equation (10) after recalculating it according to equation (13) for metal powder (the rough surface). The yellow line shows the theoretical dependence of emissivity on temperature, which is described by equation (11) after recalculating it according to equation (13) for metal powder.

As can be seen from Figure 4, the emissivity of 316L powder steel varies from 0.29 to 0.47 in the temperature range from 333 K to 1174 K when using the theoretical function (11) and recalculating its value according to formula (13) for a non-smooth surface. When using the theoretical functions (12) and (13), the emissivity of 316L powder steel varies from 0.34 to 0.53 in the temperature range from 333 K to 1174 K. The experimental results showed that the experimental emissivity values of 316L powder steel varies from 0.31 to 0.58 in the temperature range from 333 K to 1174 K (red line in Fig. 4).

Having analyzed the obtained results of modeling theoretical functions that describe the characteristics of changes in the emissivity of 316L powder steel and comparing tchem with the experimental results, it can be seen (Fig. 4) that the theoretical values of the emissivity of powder steel are close to the experimental results obtained. Moreover, the deviations of the theoretical and experimental values of the emissivity coefficients do not exceed the expanded uncertainty value of ±0.06 (in Fig. 4 there are purple error bars from experimental data). Also, as can be seen from Fig. 4, in the temperature range from 333 K to 680 K, the theoretical values of the emissivity of 316L powder steel are very close to the experimental values when they were described by equation (11) using equation (13) for non-smooth metal surfaces (metal powder). And in the temperature range from 680 K to 1174 K the theoretical characteristic described by equation (12) using equation (13) is closer to the experimental value of the emissivity of 316L powder steel. The increase in emissivity values that were observed in experimental studies after the temperature of 700 K is most likely due to the onset of oxidation processes in 316L powder steel, which manifests themselves when metal powder samples are heated to higher temperatures.

Based on the above results, we can assume that theoretical equations (11), (12), and (13) can be used to determine the emissivity of 316L powder steel when introducing machine learning elements into metal additive manufacturing processes. But it should also be noted that the only way to obtain reliable data on the emissivity characteristics of metals is through experimentation.

3. Conclusions

Thus, the article examined the possibility of theoretically determining the value of the emissivity of solid metals through the value of the electrical resistivity of the metal and the temperature of the object. There are several analytic expressions that can describe the characteristics of changes in the emissivity of metals with an increase (change) in the temperature of the metal under study. Moreover, these expressions (10)–(12) describe the characteristics of the change in emissivity for smooth hard metal surfaces. Therefore, equation (13) was proposed to convert the emissivity values of smooth metal surfaces into those of rough metal surfaces or powdered metal materials. When comparing the obtained theoretical characteristics of changes in the emissivity of powder steel 316L with the experimental characteristics, we find that the results were close in value and do not exceed the expanded uncertainty value of 0.06. At the same time, to describe the characteristics of changes in the emissivity of 316L powder steel in the temperature range from 333 K to 680 K, equations (11) and (13) are better suited. To model the characteristics of changes in the emissivity of 316L powder steel in the temperature range from 680 K to 1174 K, the characteristics described by equations (12) and (13) were closer to the experimental data.

The equation for converting the emissivity of smooth, hard surfaces to powdery or rough surfaces (13) is supported by experimental data for many metals, such as nichrome, nickel-cobalt alloy, stainless steel, brass, and aluminum. However, there are also materials for which it is impossible to quantitatively describe the dependence of emissivity on the nature of the surface, as well as on its temperature and degree of oxidation. Therefore, the best way to determine the emissivity values is to conduct an experimental study.

In our case, as shown by experimental studies of the emissivity of 316L stainless steel powder, equations (11), (12), and (13) can be used in machine learning algorithms to predict (determine) the emissivity.

References

[1] AISI Type 316L Stainless Steel [https://www.matweb.com/search/datasheet_print.aspx?matguid=1336be6d0c594b55afb5ca8bf1f3e042].

[2] Boley C. D. et al.: Metal powder absorptivity: modeling and experiment. Applied optics 55(23), 2016, 6496–6500.

[3] Cai Y. et al.: A review of in-situ monitoring and process control system in metal-based laser additive manufacturing. Journal of Manufacturing Systems 70, 2023, 309–326.

[4] Gusarov A. V. et al.: Normal-directional and normal-hemispherical reflectances of micron-and submicron-sized powder beds at 633 and 790 nm. Journal of applied physics 99(11), 2006.

[5] Gusarov A. V.: Radiative transfer, absorption, and reflection by metal powder beds in laser powder-bed processing. Journal of Quantitative Spectroscopy and Radiative Transfer 257, 2020, 107366.

[6] Modest M. F., Mazumder S.: Radiative heat transfer. Academic press, 2021.

[7] Mohr G. et al.: Experimental determination of the emissivity of powder layers and bulk material in laser powder bed fusion using infrared thermography and thermocouples. Metals 10(11), 2020, 1546.

[8] Palik E. D.: Handbook of optical constants of solids. Academic press, 1998.

[9] Setién-Fernández I. et al.: Spectral emissivity of copper and nickel in the mid-infrared range between 250 and 900 C. International Journal of Heat and Mass Transfer 71, 2014, 549–554.

[10] Shvarev K. M., Baum B. A.: Estimation of radiative characteristics of metals in the framework of classical electronic theory. Soviet Physics Journal 21(1), 1978, 1–4.

[11] Son E.: Measurement of Flame Temperature by the Spectral-Line Reversal Method. In Physical Mechanics. Begell House, 2012.

[12] Tilley R. J.: Colour and the optical properties of materials. John Wiley & Sons, 2020.

[13] Vasilevskyi O. M., Koval M., Kravets S.: Indicators of reproducibility and suitability for assessing the quality of production services. Acta Imeko 10(4), 2021, 54–61.

[14] Vasilevskyi O. M.: Advanced mathematical model of measuring the starting torque motors. Technical Electrodynamics 6, 2013, 76–81.

[15] Vasilevskyi O. M.: Assessing the level of confidence for expressing extended uncertainty: a model based on control errors in the measurement of ion activity. Acta Imeko 10(2), 2021, 199–203.

[16] Vollmer M., Möllmann, K. P.: Infrared Thermal Imaging: Fundamentals, Research and Applications. John Wiley & Sons, 2018.

[17] Vollmer M.: Infrared thermal imaging. In Computer Vision: A Reference Guide. Cham: Springer International Publishing, 2020.

[18] Wang J. et al.: Emissivity calculation for a finite circular array of pyramidal absorbers based on Kirchhoff's law of thermal radiation. IEEE transactions on antennas and propagation 58(4), 2010, 1173–1180.

[19] Wang R. et al.: Real-time process monitoring and closed-loop control on laser power via a customized laser powder bed fusion platform. Additive Manufacturing 66, 2023, 103449.

[20] Watanabe H. et al.: Spectral emissivity measurements. In Experimental Methods in the Physical Sciences 46, 2014, 333–366.

[21] Zhang Z. M., Lee B. J.: Theory of thermal radiation and radiative properties. Experimental Methods in the Physical Sciences 42, 2009, 73–132.

D.Sc. Eng. Oleksandr Vasilevskyi
e-mail: oleksandr.vasilevskyi@austin.utexas.edu

Doctor of engineering sciences, professor (full), Senior Researcher in the Walker Department of Mechanical Engineering at the University of Texas at Austin (USA). Dr. Vasilevskyi's research focuses on the development of instruments for measuring physical quantities, measurement systems, and metrological support to ensure the unity of measurements. Academician of the Academy of Metrology of Ukraine, an official representative from Ukraine in the IMEKO. Member of the Institute of Electrical and Electronics Engineers (IEEE). The badge of the Ministry of Education and Science of Ukraine "For scientific and educational achievements" (2020). Laureate of the Prize of the Verkhovna Rada of Ukraine for young scientists (2019).

His research interests include the design and development of measurement techniques, equipment for controlling additive manufacturing, equipment for measuring biophysical characteristics, automatic control systems for electric motors, instruments for measuring ion concentrations, and methodologies for evaluating measurement uncertainty.

https://orcid.org/0000-0002-8618-0377

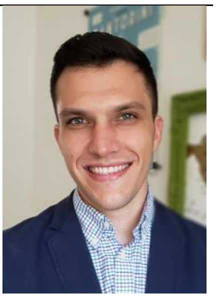
Dr. Michael Cullinan
e-mail: michael.cullinan@austin.utexas.edu

Dr. Michael Cullinan is an assistant profesor in the Walker Department of Mechanical Engineering and the Director of the Nanoscale Design and Manufacturing Laboratory at the University of Texas at Austin (USA). Dr. Cullinan's research focuses on the development of novel nanomanu–facturing systems and on finding ways to exploit nanoscale physical phenomena in order to improve existing macroscale devices and to create novel micro- and nanoscale devices for energy and sensing applications.

His research interests include the design and development of nanomanufacturing processes and equipment, the application of nanoscale science in engineering, the engineering of thin films, nanotubes and nanowires, the manufacturing and assembly of nanostructured materials, and the design of micro/nanoscale machine elements for mechanical sensors and energy systems.

https://orcid.org/0000-0001-8256-7921

Dr. Jared Allison
e-mail: jared.allison@utexas.edu



Dr. Jared Allison earned bachelor's degrees in mechanical and aerospace engineering from Oklahoma State University in 2015. He then attended the University of Texas at Austin where he received a master's degree in mechanical engineering in 2017 and a Ph.D. in mechanical engineering in 2020. His research experience lies at the intersection of design for additive manufacturing and new process development. Upon completing his Ph.D., Dr. Allison assumed the role of operations manager at the Center for Additive Manufacturing and Design Innovation where he has developed expertise in part fabrication, applications research, and instruction for commercial polymer and metal additive manufacturing processes.

https://orcid.org/0000-0001-7388-0510