Results of Studies on the Emissivity of Metal Powder for Implementing an Intelligent Control Approach in Additive Manufacturing

Oleksandr Vasilevskyi*[a], Michael Cullinan[a], Jared Allison [a], Leonid Polishchuk[b], Orken Mamyrbayev[c], Konrad Gromaszek[d], Sofia Dembitska[b]

[a]The University of Texas at Austin, Walker Department of Mechanical Engineering, 204 E Dean Keeton, Austin, TX 78712, USA; [b]Vinnytsia National Technical University Ave. Khmelnytskeshose, 95 Vinnytsia, 21021 Ukraine; [c]Institute of Information and Computational Technologies, Almaty, Kazakhstan; [d]Lublin University of Technology, Nadbystrzycka 38A, 20-618 Lublin, Poland;

ABSTRACT

In this study, the emissivity values of metal powder were examined by measuring reference temperature values using thermocouples, an infrared camera and aluminium foil to determine the reflection temperature. This enabled the testing of a methodology for determining emissivity in order to implement an intelligent control approach in additive manufacturing. The research established emissivity values for the surface of 316L powder steel that range from 0.33 to 0.46 in the temperature range from 50 to 600°C. The proposed approach allows the calibration of an infrared camera to accurately determine the temperature values of metal surfaces, which opens up the possibility of using the measurement results for intelligent control of laser power in additive manufacturing.

Keywords: additive manufacturing, infrared camera, intelligent control, 316L powder steel, emissivity, remote temperature measurement

1. INTRODUCTION

Widespread adoption of metals additive manufacturing (AM) for functional, end-use parts relies upon our ability to fabricate high-quality parts consistently without iterative testing cycles. Significant recent progress in in-situ process monitoring, part and process qualification, and design guidance aims to address this challenge, but it is difficult to generalize much of this work to different machines, different builds, or parts with different geometries. We propose a transfer learning approach for enhancing part quality and consistency across builds, machines, and part geometries. The approach is based on an intelligent, machine learning-enabled control methodology and in-situ optical metrology. The approach enables feed-forward control of melt pool geometry based on detailed models encompassing extensive physics-based modeling and empirical qualification, coupled with inexpensive transfer learning models that can correct for build-to-build, machine-to-machine, and part-to-part variations[1-3].

The central focus of the effort is the construction of transfer learning models to predict and control melt pool geometry, and by extension, part geometry and quality in metal powder bed fusion (PBF) processes. The transfer learning model encompasses three constituent model-based building blocks. The first building block is a data-driven surrogate model, based on detailed physics-based simulations connecting part geometry, material properties, and laser processing parameters to the resulting depth and surface temperatures of the melt pool. This model predicts melt pool geometry as a function of process parameters, such as laser power, that are adjustable in real-time, as well as spatial changes in part geometry, such as the presence of thin regions and unsupported overhangs that require different processing parameters and melt pool characteristics[2-3]. Performance goals include geometric accuracy and layer-to-layer adhesion, and the surrogate model enables rapid prediction for monitoring and optimal control. The second building block is a surrogate model corrector that enhances the accuracy of the data-driven surrogate model via experimental data acquired from a fully instrumented exemplar metals AM (PBF) machine. The result is a calibrated surrogate model that can predict melt pool depth and surface temperatures with high levels of accuracy for the exemplar machine, across a range of part geometries, materials, and laser powers[4]. Finally, the third building block is a transfer learning model based on empirical data from a specific build that can rapidly update the predictions of the Stage Two surrogate model to enhance accuracy when moving from build to build or machine to machine.

*e-mail: oleksandr.vasilevskyi@austin.utexas.edu; phone +17373284605

Photonics Applications in Astronomy, Communications, Industry, and High Energy Physics Experiments 2024,
edited by Ryszard S. Romaniuk, Andrzej Smolarz, Waldemar Wójcik, Proc. of SPIE
Vol. 13400, 134000Q · © 2024 SPIE · 0277-786X · doi: 10.1117/12.3058548

This article discusses the first stage of the second building block of creating a calibration model, which consists of developing an algorithm and methodology for experimentally determining the emissivity of powder metals.

2. EXPERIMENTAL

The purpose of the study was to test the methodology for determining the emissivity of 316L powder steel at different values of the surface temperature of the metal powder for the subsequent use of the results obtained in transfer learning algorithms.

Materials and methods. The emissivity of a black body is $\varepsilon = 1$, and the emissivity of real bodies is smaller $\varepsilon < 1$[5-6]. The emissivity ε of solid objects is often treated as a constant and independent of the wavelength within short intervals, in which IR cameras work[7-8]. In doing so, real bodies are assumed to be grey bodies[8]. As stated in the literature sources[7-9], the emissivity of a real object depends on several factors: material, temperature, surface condition (surface roughness and oxidation state), wavelength, and viewing angle. Known reference emissivity values of various materials are generally considered to be fixed perpendicular to the surface of the target object[10], but they are stated without specifying combinations or expanded measurement uncertainty. It is also known that metals and their alloys have significantly low emissivity values and undergo strong changes due to the state of the surface[11]. Therefore, studying the values of the emissivity when heating metal powders to certain temperatures and calculating the uncertainty values (indicating the intervals in which the emissivity can be located) is an important task when implementing additive manufacturing control systems using machine learning.

Since 316L powder steel is often used in additive manufacturing, experimental studies were conducted to determine the emissivity using the FLIR A700 infrared camera. They consisted of heating powder steel type 316L to certain precisely set temperature values (133°C, 141°C, 300°C, 500°C) using a special heating chamber Paragon, measuring the reference temperature value using an additional temperature measurement channel with a precision sensor (thermocouple) and determining the temperature values of heated objects using an infrared camera (based on photographs taken). In this case, using the FLIR Research Studio software for the FLIR A700 infrared camera, different values of the emissivity were set[12-13].

Based on the conducted temperature measurement studies, multiple temperature measurements of powdered steel 316L were obtained an algorithm for determining the emissivity of the FLIR A700 infrared camera was proposed, which can be used in a control methodology with support for machine learning[14-15].

Results. In the first stage, a sample of powder steel type 316L was prepared, which was placed in a special ceramic container. A precision measuring channel with a thermocouple was used to determine the reference value of powdered steel temperature. The temperature measurement accuracy of which is ±1.1 °C. The first step in determining the surface temperature of metal powder using an infrared camera was to heat a ceramic container with steel powder on an electric stove with a built-in temperature controller. In this case, the thermocouple was placed in powdered steel (Fig. 1).

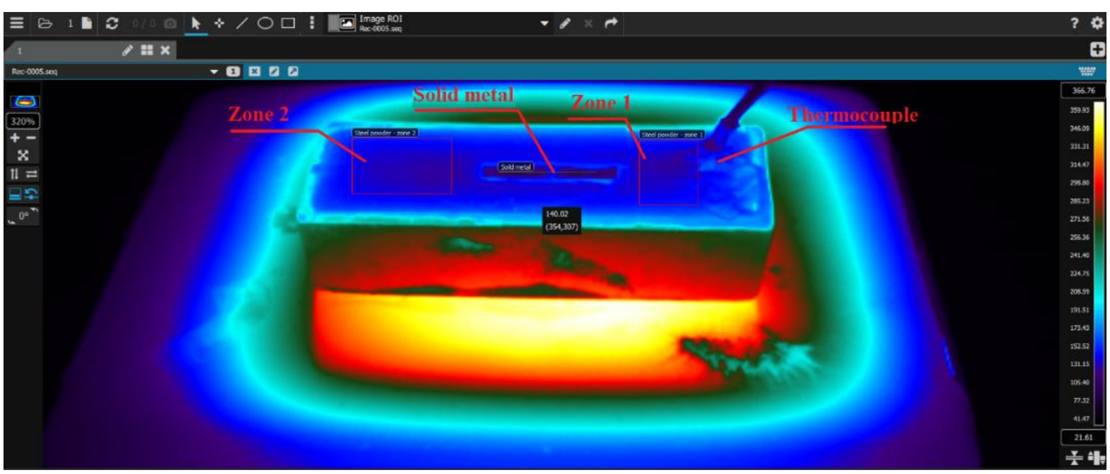

Fig. 1 – Snapshot of the IR Camera showing the measurement zones

Preliminarily, the ambient temperature was measured, which was equal to 23.2°C, the distance from the camera to the measurement object, which was 0.3 m, and the relative humidity, which corresponded to a value of 55%.

Using the FLIR A700 IR camera, images of the measurement object were taken at the measured reference temperatures (133 °C and 141 °C) of 316L powdered steel. After processing the obtained images at the specified temperature reference values using the FLIR Research Studio software, multiple temperature measurements of 316L powder steel were obtained. The average values of the measured temperature using an IR camera for different values of the emissivity are presented in Tables 1 - 6. The emissivity was selected in the FLIR Research Studio software environment so that the temperature range of the IR camera overlapped the reference temperature values obtained by the thermocouple, taking into account the Stefan-Boltzmann law[16-17].

Table 1. At the reference temperature value of 133 °C, (Experiment 1)

Emissivity	0.34	0.35	**0.36**	0.37	0.38	0.39	0.40	0.41
Steel power - Zone 1, °C	135.55	134.18	**132.86**	131.59	130.36	129.18	128.04	126.93
Steel power - Zone 2, °C	136.32	134.94	**133.62**	132.34	131.10	129.92	128.77	127.66

Table 2. At the reference temperature value of 133 °C, (Experiment 2)

Emissivity	0.34	**0.35**	**0.36**	0.37	0.38	0.39	0.40
Steel power - Zone 1, °C	135.10	133.73	**132.43**	131.15	129.93	128.76	127.62
Steel power - Zone 2, °C	134.33	**132.97**	131.66	130.40	129.19	128.01	126.89

Table 3. At the reference temperature value of 133 °C, (Experiment 3)

Emissivity	0.34	0.35	**0.36**	**0.37**	0.38	0.39	0.40	0.41
Steel power - Zone 1, °C	136.04	134.66	**133.34**	132.06	130.84	129.65	128.50	127.39
Steel power - Zone 2, °C	136.44	135.06	133.73	**132.45**	131.22	130.03	128.88	127.77

Table 4. At the reference temperature value of 133 °C, (Experiment 4)

Emissivity	0.34	**0.35**	0.36	0.37	0.38	0.39	0.40
Steel power - Zone 1, °C	134.49	**133.13**	131.82	130.56	129.34	128.17	127.04
Steel power - Zone 2, °C	134.41	**133.05**	131.74	130.48	129.27	128.09	126.96

Table 5. At the reference temperature value of 141 °C, (Experiment 1)

Emissivity	0.32	**0.33**	0.34	0.35	**0.36**	0.37	0.38	0.39	0.40
Steel power - Zone 1, °C	141.94	**140.42**	138.96	137.56	136.20	134.90	133.64	132.43	131.26
Steel power - Zone 2, °C	146.26	144.70	143.19	141.74	**140.35**	139.01	137.71	136.47	135.26

Table 6. At the reference temperature value of 141 °C, (Experiment 2)

Emissivity	0.32	**0.33**	0.34	0.35	0.36	**0.37**	0.38	0.39
Steel power - Zone 1, °C	141.82	**140.30**	138.84	137.43	136.08	134.78	133.53	132.31
Steel power - Zone 2, °C	148.42	146.83	145.30	143.83	142.42	**141.06**	139.74	138.48

From the experimental data obtained for the selected areas (Tables 1 – 4) it was clear that with the measured reference temperature value of 133 °C, we obtained the range of measured temperatures of 316L powder steel using an IR camera, into which the specified reference temperature value falls. In this case, the emissivity values of 316L powder steel were in the range from 0.35 to 0.37 for Zone 1 and Zone 2 (Fig. 1).

From the experimental data obtained for the selected areas (Tables 5 and 6), it can be seen that with a measured reference temperature value of 141 °C, we obtained a range of measured steel powder temperatures using an IR camera, in which the specified reference temperature value falls. In this case, the emissivity values of 316L powder steel were in the range from 0.33 to 0.37 for Zone 1 and Zone 2 (Fig. 1).

The standard uncertainty of type A temperature measurement was calculated by the formula $u_A(\bar{x}) = \left[\frac{\sum_{i=1}^{n}(x_i-\bar{x})^2}{n(n-1)}\right]^{\frac{1}{2}}$, where x_i is quantity of measurements, $\bar{x}$ is mean value, n is the number of values in the sample[18-21].

The value of the standard measurement uncertainty of type A, calculated by the formula for Zones 1 and 2 (Fig. 1) for the reference temperature value of 133 °C were $u_{A_{133z1exp1}}(\bar{x})$ =1.6 °C, $u_{A_{133z2exp1}}(\bar{x})$ =1.8 °C, $u_{A_{133z1exp2}}(\bar{x})$ =1.7 °C, $u_{A_{133z2exp2}}(\bar{x})$ =1.9 °C, $u_{A_{133z1exp3}}(\bar{x})$ =1.64 °C, $u_{A_{133z2exp3}}(\bar{x})$ =1.8 °C, $u_{A_{133z1exp4}}(\bar{x})$ =1.7 °C and $u_{A_{133z2exp4}}(\bar{x})$ =1.9 °C. And for the reference temperature value of 141 °C were $u_{A_{141z1exp1}}(\bar{x})$ = = 1.93 °C, $u_{A_{141z2exp1}}(\bar{x})$ = = 1.72 °C, $u_{A_{141z1exp2}}(\bar{x})$ = = 1.97 °C, and $u_{A_{141z2exp2}}(\bar{x})$ = = 1.46 °C.

Experimental values of the emissivity of 316L powder steel within the temperature range of 132 °C to 142 °C were presented in Fig. 2.

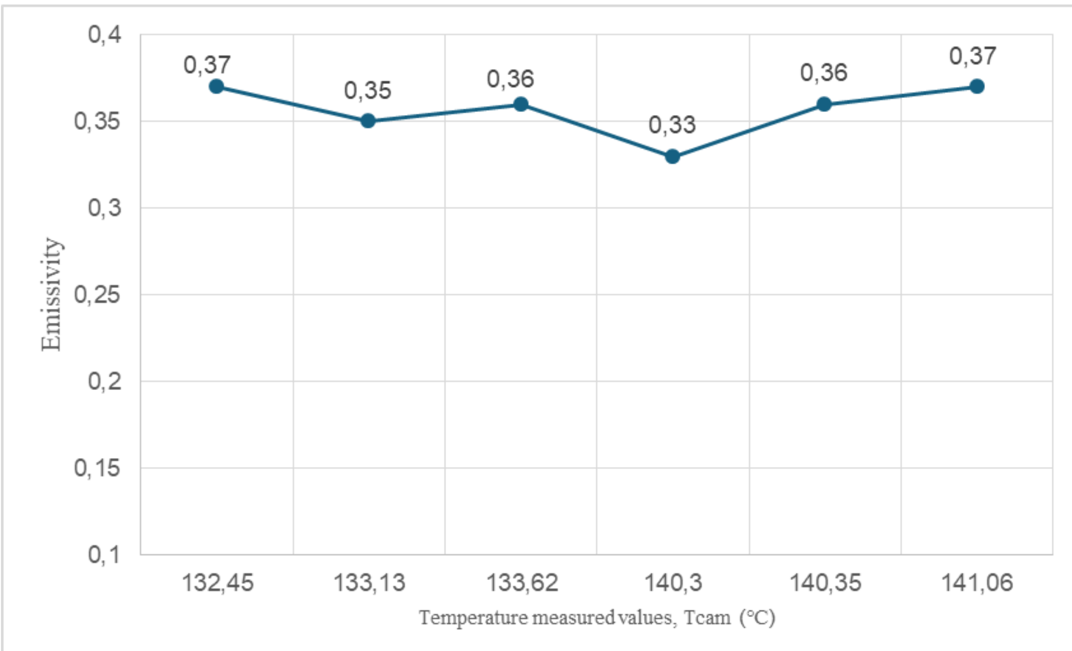

Figure 2. Experimental values of the emissivity of 316L powder steel in the temperature range from 132 °C to 142 °C

Thus, the average emissivity value, which was determined from the average temperature values from the selected area was ε = 0.36.

In the next stage of research, the container with 316L powder steel was placed in the furnace Paragon with a Sentry 2.0 controller to heat the samples to higher temperatures, first to 400 °C and then to 600 °C. For measuring the reference temperature value, the same temperature-measuring channel with high-precision thermocouples was used. When powder steel was heated in a furnace to a certain temperature, multiple images were taken using an IR camera.

One of the important steps in accurately measuring the temperature and emissivity of metal surfaces is the correct determination of the reflection temperature. According to the international standard ISO 18434-1[22], there are several ways to determine reflection temperature. The first of these is the use of a blackbody. In this case, the measured value of the black body temperature using a reference measuring channel, for example, using a thermocouple, is accepted as the reflection temperature, the value of which is set in the IR camera settings. If using the blackbody is difficult or impossible, then another method can be used to determine the temperature of the reflection. This is the so-called aluminum foil reflection method. The reflector is placed in the camera's field of view in the same plane as the surface of the object under study. To determine the reflection temperature, we used aluminum foil as the reflector.

At the same time, several samples of 316L powder steel were heated in the Paragon oven to temperatures of 400 °C and 600 °C, the temperature of which was also measured using thermocouples (Fig. 3).

As a result of processing the photographs taken, the following results were obtained.

The average emissivity of powder steel 316L was 0.43 at a reference temperature of 400 °C. And at a reference temperature of 600 °C, the average value of the emissivity of powder steel was 0.46.

Considering the experimental data obtained, a characteristic of the change in the emissivity values of 316L powder steel after repeated heating in the temperature range from 50 °C to 606 °C was constructed, which is shown in Fig. 4.

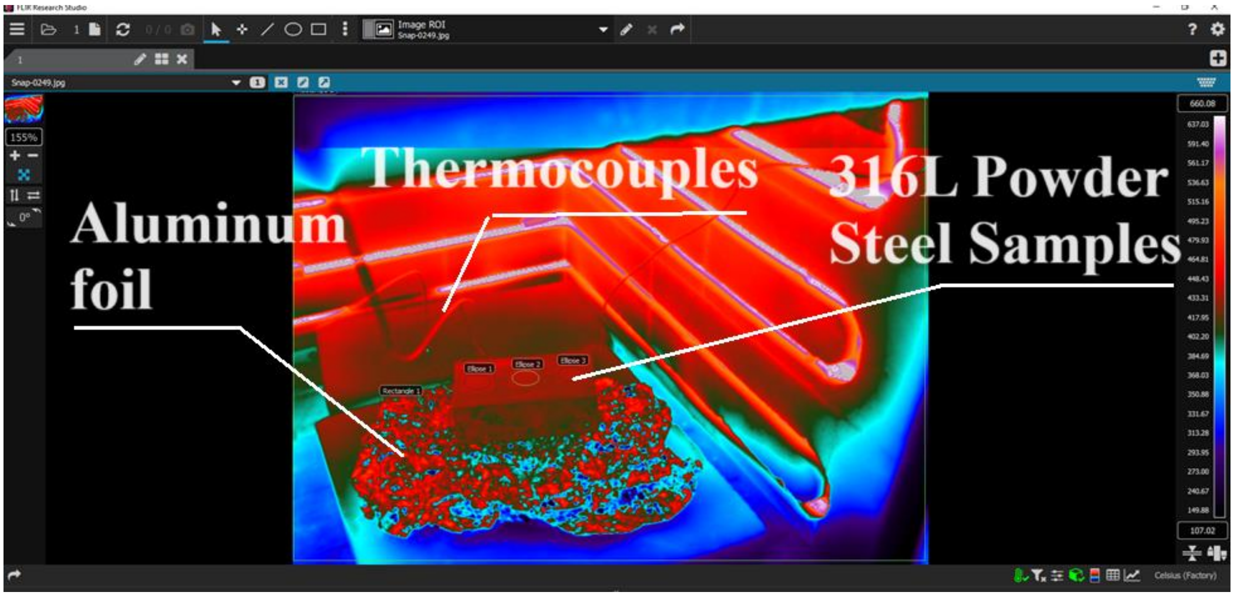

Fig. 3 - Photo of the research object at a temperature of 400 °C

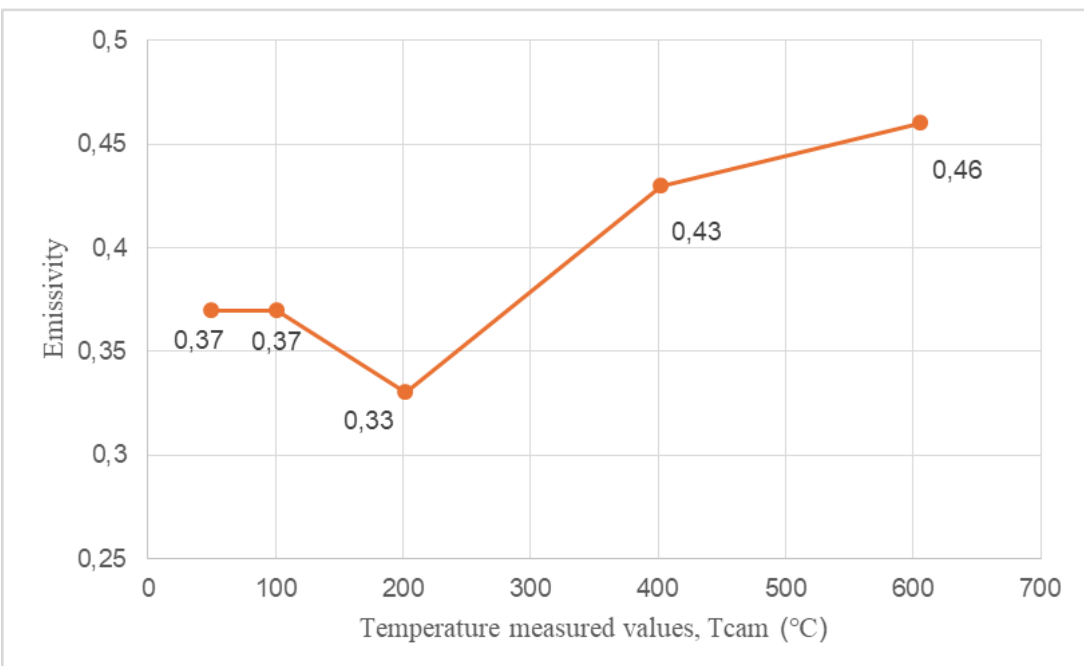

Fig. 4 – Emissivity values of powder steel 316L in the temperature range from 50 °C to 606 °C

As a result of experimental studies of the emissivity of 316L powder steel using precision thermocouples, the infrared camera, and aluminum foil as the reflector, it was found that in the temperature range from 50 °C to 606 °C, the emissivity values vary from 0.33 to 0.46. In this case, the expanded measurement uncertainty at each reference point of the study does not exceed ±0.06. The increase in the emissivity coefficient of 316L powder steel may be due to the slight influence of oxidation of the upper layer of metal powder when it is heated to temperatures above 500 °C.

3. CONCLUSIONS

Thus, the proposed technique for measuring the temperature and emissivity of metal powder surfaces makes it possible to ensure uniformity of measurements in additive manufacturing, as well as use the measurement results to control laser power. From the research results it is clear that there is no single constant value of the emissivity, but there is a range of values in which the actual value of the emissivity may lie depending on the surface temperature of the object of study.

Since the studies were conducted to implement intelligent control processes in additive manufacturing supported by transfer learning, the methodology for determining the emissivity of metal powder using the infrared camera was tested based on the experiments conducted. This methodology enables the automation of the procedure for remotely determining the temperature of metal surfaces to control laser power based on known emissivity depending on the temperature range. The obtained emissivity of metal powder surfaces and measurement uncertainty values serve as reference data for the knowledge base on which machine learning algorithms will be implemented.

REFERENCES

[1] Liu, S., Stebner, A. P., Kappes, B. B. and Zhang X., "Machine learning for knowledge transfer across multiple metals additive manufacturing printers," Additive Manufacturing 39, 101877 (2021). https://doi.org/10.1016/j.addma.2021.101877

[2] Jenks, C., "Basic Research Needs for Transformative Manufacturing: Report of the Basic Energy Sciences Workshop on Basic Research Needs for Transformative Manufacturing," (2020). https://doi.org/10.2172/1618123

[3] McCann, R., Obeidi, M. A., Hughes, C., McCarthy, É., Darragh S. Egan, D. S., Vijayaraghavan, R. K., Joshi, A. M., Garzon, V. A., Dowling, D. P., McNally, P. J., Brabazon, D., "In-situ sensing, process monitoring and machine control in Laser Powder Bed Fusion: A review." Additive Manufacturing 45, 102058 (2021). https://doi.org/10.1016/j.addma.2021.102058

[4] Vasilevskyi, O., Cullinan, M. and Allison, J., "Adaptive intelligent control of metal powder bed fusion via transfer learning Adaptive intelligent control of metal powder bed fusion via transfer learning," VII International Scientific and Practical Conference, Mechatronic Systems: Innovations and Engineering (MSIE-2023), Kyiv, Ukraine, 26-27 (2023). DOI: 10.5281/zenodo.10202154.

[5] Heigel, J. and Whitenton, E., "Measurement of thermal processing variability in powder bed fusion," In Proceedings of the 2018 ASPE and Euspen Summer Topical Meeting-Advancing Precision in Additive Manufacturing, Berkeley, USA, 22-25 (2018).

[6] Schuster, N. and Kolobrodov, V., [Infraredthermography: textbook], Wiley-VCH: Weinheim, Germany, (2004).

[7] Mohr, G., Nowakowski, S., Altenburg, S., Maierhofer, C. and Hilgenberg, K, "Experimental determination of the emissivity of powder layers and bulk material in laser powder bed fusion using infrared thermography and thermocouples," Metals 10(11), 1546 (2020). https://doi.org/10.3390/met10111546

[8] Usamentiaga, R., Venegas, P., Guerediaga, J., Vega, L., Molleda, J. and Bulnes F., "Infrared thermography for temperature measurement and non-destructive testing," *Sensors* 14(7), 12305-12348 (2014). https://doi.org/10.3390/s140712305

[9] Vollmer, M., "Infrared thermal imaging," In Computer Vision: A Reference Guide, Cham: Springer International Publishing, 666-670 (2021). https://doi.org/10.1007/978-3-030-63416-2_844

[10] Siegel, R., Howell, J. and Lohrengel, J., "Wärmeübertragung Durch Strahlung," Wärme- Und Stoffübertragung, (1988). https://doi.org/10.1007/978-3-642-83267-3

[11] Glueckert U., [Detection and measurement of thermal radiation. A practical introduction to pyrometry and thermography. Erfassung und Messung von Waermestrahlung. Eine praktische Einfuehrung in die Pyrometrie und Thermographie.], Germany, (1992).

[12] Azarov, O. D., Murashchenko, O.G. and etc. "Method of glitch reduction in DAC with weight redundancy," Proc. SPIE 9816, Optical Fibers and Their Applications 2015, 98161T (2015). https://doi.org/10.1117/12.2229045

[13] Hotra Oleksandra, Kovtun Svitlana, etc. "Analysis of Low-Density Heat Flux Data by the Wavelet Method," Energies 16(1), 1-16, (2023).
[14] Vasilevskyi, O. M., Yakovlev, M. Y., Kulakov, P. I. "Spectral method to evaluate the uncertainty of dynamic measurements," Technical Electrodynamics 4, 72–78 (2017). DOI: 10.15407/techned2017.04.072,
[15] Zvirko, O., Tsyrulnyk, O. and Polishchuk, L. "Assessment of Hydrogen Assisted Degradation of Stacker Conveyor Boom Steel," Lecture Notes in Intelligent Transportation and Infrastructure F1379, 200–207 (2023).
[16] Zhanabaev, Z. Z., Turlykozhayeva, D. A. and etc. "Current and capacitance hysteresis in porous semiconductor nanofilms," Physical Sciences and Technology 7(3-4), 37-43 (2020).
[17] Andrushchenko, M., Selivanova, K., and etc. "Hand movement disorders tracking by smartphone based on computer vision methods," Informatyka, Automatyka, Pomiary w Gospodarce i Ochronie Środowiska 14(2), 5-10 (2024).
[18] Vasilevskyi, O., "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), 199-203 (2021). DOI: 10.21014/acta_imeko.v10i2.810
[19] BIPM, IEC, IFCC, ILAC, ISO, IUPAC, IUPAP, and OIML. Evaluation of measurement data – Guide to the expression of uncertainty in measurement. Joint Committee for Guides in Metrology, JCGM 100, (2008).
[20] Vasilevskyi, O., Koval, M. and Kravets, S., "Indicators of reproducibility and suitability for assessing the quality of production services," Acta IMEKO 10(4), 54-61 (2021). DOI: 10.21014/acta_imeko.v10i4.814
[21] ISO/IEC Guide 98-3: Uncertainty of measurement – Part 3: Guide to the expression of uncertainty in measurement (GUM:1995), 120 (2008).
[22] ISO 18434-1:2008. Condition monitoring and diagnostics of machines – Thermography. Part 1: General procedures, 24 (2008).