FLASH-PULSE THERMOGRAPHY EVALUATION OF COLD SPRAY 316L STEEL COATINGS

[1]Alexey MOSKOVCHENKO, [1]Michal ŠVANTNER, [2]Marek VOSTŘÁK, [2]Žaneta DLOUHÁ, [2]Šárka HOUDKOVÁ

[1] New Technologies-Research Centre, University of West Bohemia, Pilsen, Czech Republic, EU, alexeym@ntc.zcu.cz, msvantne@ntc.zcu.cz

[2] Research and Testing Institute Plzeň, Pilsen, Czech Republic, EU, vostrak@vzuplzen.cz, dlouha@vzuplzen.cz, houdkova@vzuplzen.cz

https://doi.org/10.37904/metal.2025.5083

Abstract

This study investigates the application of infrared (IR) thermography for evaluating thermal-sprayed coatings, focusing on distinguishing coatings subjected to different thermal treatments and varying porosity levels. Experimental thermographic analysis demonstrated the capability of IR thermography to differentiate between coating variants. The Fourier transform method and phase analysis at low frequencies proved remarkably effective. This approach enabled the visualization of areas with differing thicknesses in the thermographic images and facilitated detailed analysis through phase-frequency plots. The results highlight the potential of IR thermography as a powerful, non-destructive tool for characterizing thermal-sprayed coatings, offering insights into their structural and thermal properties. This method holds promise for quality control and optimization in industrial applications involving thermal spray processes.

Keywords: Thermal spraying, coatings, infrared thermography, porosity, IRNDT, active thermography, thermographic testing

1. INTRODUCTION

Cold spray technology has emerged as a pivotal solid-state coating deposition method, particularly for 316L stainless steel, owing to its ability to produce dense, oxidation-resistant coatings with superior mechanical properties. These coatings are increasingly deployed in demanding industrial applications, such as aerospace, marine, and energy systems, where corrosion resistance, wear protection, and structural integrity are critical [1]. However, the performance of cold spray coatings is inherently tied to their microstructural quality, particularly porosity, which arises from imperfect particle bonding during deposition and is further influenced by post-deposition thermal treatments [2]. Traditional quality control methods, such as metallographic microscopy and ultrasonic testing, face limitations in non-destructively assessing subsurface porosity or correlating it with processing parameters, creating a pressing need for advanced evaluation techniques [3].

Non-destructive testing (NDT) methods like flash-pulse thermography (FPT) have gained traction for coating characterization due to their rapid, full-field imaging capabilities and sensitivity to thermal property variations. FPT employs short-duration thermal excitation and infrared (IR) imaging to capture transient thermal responses, enabling the detection of subsurface defects and thickness variations [4,5]. Prior studies have successfully applied thermography to evaluate thermal barrier coatings [6] and polymer composites [7], with a focus on defect detection (e.g., delamination, cracks) or thickness measurement. However, porosity evaluation, especially as a function of thermal treatment parameters, remains underexplored, particularly for cold-sprayed metallic coatings. This gap is significant, as post-spray heat treatments are routinely used to modify porosity and enhance coating adhesion [8], yet existing NDT methods lack the resolution to quantify these microstructural changes non-destructively.

Thermographic data analysis offers opportunities for quantitative characterization of materials and defects. For instance, fast Fourier transformation (FFT) and phase analysis have demonstrated potential in distinguishing regions with varying thermal diffusivity, such as thickness gradients in coatings [9], but their application to porosity evaluation remains novel. Unlike amplitude-based methods, phase analysis is less sensitive to surface emissivity variations, making it particularly suited for assessing subsurface porosity in metallic coatings [10]. This study bridges this critical gap by adapting FPT with Fourier phase analysis to quantitatively evaluate porosity in cold-sprayed 316L steel coatings as a function of thermal treatment parameters.

2. EXPERIMENTAL SETUP AND SAMPLES

Steel substrates of two grades, 11 353 and X52 steel, were selected for coating deposition. The samples represented parts of a 219 mm diameter steel pipeline with a wall thickness of 10 mm, which were machined into plates of 60x150 mm with a rounded surface.

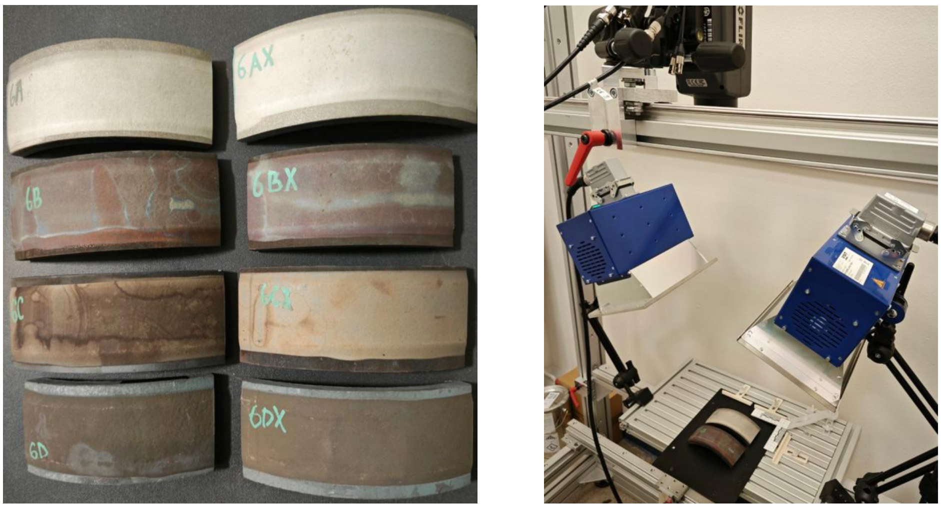
The 316L stainless steel coatings were applied using an Impact Spray System (Gun 6/11 EvoCSII) under the following parameters:

- Carrier gas (N_2) pressure: 50–60 bar
- Preheating temperature: 1000–1100°C
- Standoff distance: 30 cm
- Powder feed rate: 50 g/min
- Coating thickness: ~1.5 mm

To investigate the relationship between thermal treatment and coating porosity, four distinct heat treatment protocols were applied to separate sets of coated samples:

- As-sprayed (No treatment): Baseline condition without post-processing.
- 600°C: Annealed at 600°C for 1 hour in air, followed by air cooling.
- 800°C: Annealed at 800°C for 1 hour in air, followed by air cooling.
- 1000°C: Annealed at 1000°C for 1 hour in air, followed by air cooling.

Flash-Pulse Thermography Inspection. The coated samples were evaluated using a flash-pulse thermography (FPT) system configured as follows: **Excitation source:** High-energy Hensel Tria 6000-S Power Pack with 2x flash VH3-6000 heads (2x50% connection). **IR camera:** FLIR A6751 with a 25 mm lens and spectral range 3–5 µm. A photo of the samples and the experimental setup is shown in (**Figure 1**).



a) b)

Figure 1 Photo of samples (a) and experimental setup (b)

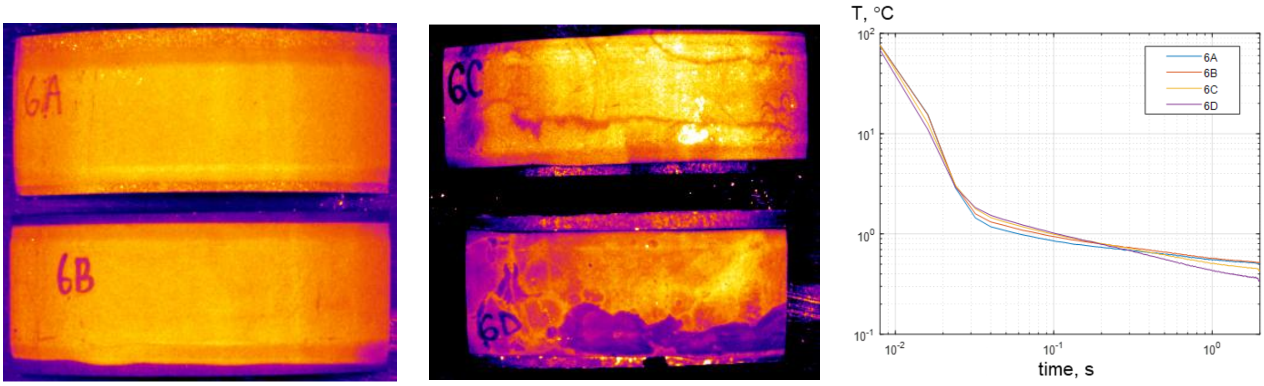
Acquisition parameters:

- Frame rate: 125 Hz
- Resolution: 640 × 512 pixels
- Temperature range: 10–90°C

The flash lamps and camera were synchronized using an external trigger to ensure consistent timing between thermal excitation and data acquisition. Samples were positioned at a standoff distance of 70 cm from the camera, with the flash lamps angled at 30° relative to the surface. A single flash pulse was applied to uniformly heat the coating surface. The IR camera recorded the cooling transient for 8 seconds (1000 frames total), capturing the thermal decay behavior. Thermographic sequences were recorded and processed using the LabIR software, which is an internal tool of the University of West Bohemia.

3. RESULTS AND DISCUSSION

The results of the infrared thermographic inspection yielded a sequence of thermograms capturing the transient thermal response of the coatings following flash heating. Figure 2 illustrates representative thermograms for samples subjected to different heat treatments (as-sprayed, 600°C, 800°C, and 1000°C marked by 6A, 6B, 6C, and 6D, respectively) alongside their corresponding average temperature decay curves.



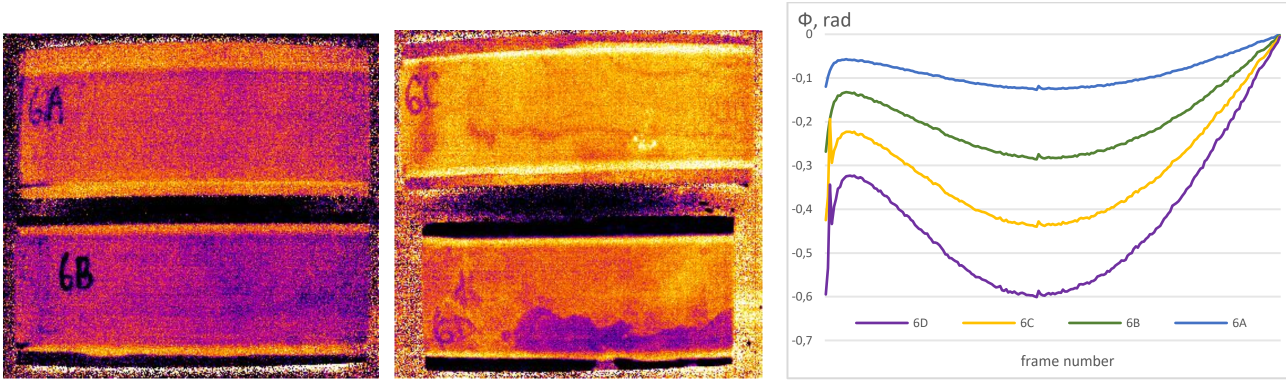
a) b) c)

Figure 2 (a-b) Thermograms of 316L coatings under varying heat treatments at t = 0.016 s post-flash, (c) Average temperature decay curves

The thermograms (**Figures 2a–2b**) reveal that the convex geometry of the rounded samples causes non-uniform heating, evident as darker peripheral regions with reduced thermal signal due to oblique flash lamp illumination and surface curvature. Samples 6C and 6D exhibit heterogeneous surface textures, likely resulting from grain growth and oxidation during high-temperature annealing.

To mitigate edge effects, temperature analysis was restricted to a central 20×20 pixel region (**Figure 2c**). The logarithmic cooling curves exhibit two distinct phases: rapid temperature drop dominated by surface heat dissipation and slower cooling governed by subsurface thermal diffusion.

The untreated sample (6A) shows the fastest initial cooling but the slowest subsequent decay, attributed to its higher porosity, which reduces thermal diffusivity by introducing air-filled voids. In contrast, heat-treated samples display elevated inflection points followed by faster temperature decay. These trends align with the known relationship between thermal treatment, porosity reduction, and enhanced thermal diffusivity in cold-sprayed coatings.



a) b) c)

Figure 3 (a-b) Examples of the phase images varying heat treatments, (c) phase sequences

The application of Fourier transform phase analysis significantly mitigates the effects of non-uniform heating and surface emissivity variations, as demonstrated in (**Figure 3**(**a–b**). Phase images reveal structural features less affected by surface artifacts, enabling more precise differentiation between heat treatment conditions. However, residual non-uniformity persists in samples 6C and 6D (**Figure 3b**), suggesting localized variations in thermophysical properties, likely arising from microstructural heterogeneity induced by high-temperature annealing. The phase images reveal systematic trends across heat treatment conditions: sample 6B (600°C) exhibits lower phase values (darker contrast) compared to 6A (as-sprayed), and 6D (1000°C) shows further reduction relative to 6C (800°C), indicating that higher annealing temperatures correlate with decreased porosity and enhanced thermal diffusivity, as reflected in the phase-angle distributions.

These differences are quantified in (**Figure 3c**), where phase plots show distinct distributions for each treatment. This relationship between phase-angle reduction and annealing temperature strongly supports the feasibility of quantitative porosity estimation using phase analysis, provided a calibrated model linking phase parameters (e.g., slope, mean angle) to porosity levels is established.

4. CONCLUSION

This study demonstrates the efficacy of flash-pulse thermography and Fourier phase analysis for evaluating porosity in cold-sprayed 316L steel coatings as a function of post-deposition heat treatment. Fourier phase analysis effectively mitigates surface emissivity artifacts and non-uniform heating, enabling robust discrimination of coatings subjected to different annealing temperatures (600°C, 800°C, 1000°C). Phase images revealed systematic trends, with lower phase angles (darker contrast) correlating to reduced porosity and improved thermal diffusivity in high-temperature-treated samples. The proposed FPT-phase analysis method offers a rapid, non-destructive alternative to traditional destructive techniques (e.g., metallography) for quality control of cold-sprayed coatings. Its ability to spatially map porosity and link it to thermal treatment parameters makes it particularly valuable for industrial applications requiring real-time process optimization.

ACKNOWLEDGEMENTS

This result was created as part of the project of the P JAC Intersectoral Cooperation for ITI CZ.02.01.01/00/23_021/0008594 European Laboratory of Applied Research of Additive Technologies for Thermal Spraying, which is co-financed by the European Union.

REFERENCES

[1] MORIDI, A., HASSANI-GANGARAJ, S.M., GUAGLIANO, M., DAO, M. Cold spray coating: review of material systems and future perspectives. Surf Eng 2014;30:369–95. https://doi.org/10.1179/1743294414Y.0000000270.

[2] AL-MANGOUR, B., MONGRAIN, R., IRISSOU, E., YUE, S. Improving the strength and corrosion resistance of 316L stainless steel for biomedical applications using cold spray. Surf Coatings Technol 2013;216:297–307. https://doi.org/10.1016/j.surfcoat.2012.11.061.

[3] ANG, A.S.M., BERNDT, C.C. A review of testing methods for thermal spray coatings. Int Mater Rev 2014;59:179–223. https://doi.org/10.1179/1743280414Y.0000000029.

[4] VAVILOV, V.P., BURLEIGH, D.D. Review of pulsed thermal NDT: Physical principles, theory and data processing. NDT E Int 2015;73:28–52. https://doi.org/10.1016/j.ndteint.2015.03.003.

[5] MALDAGUE, X. Theory and practice of infrared technology for nondestructive testing. New York: 2001.

[6] MOSKOVCHENKO, A., VAVILOV, V.P., ŠVANTNER, M., MUZIKA, L., HOUDKOVÁ, Š. Active IR Thermography Evaluation of Coating Thickness by Determining Apparent Thermal Effusivity. Materials (Basel) 2020;13:4057. https://doi.org/10.3390/ma13184057.

[7] PEETERS, J., IBARRA-CASTANEDO, C., SFARRA, S., MALDAGUE, X., DIRCKX, J.J.J., STEENACKERS, G. Robust quantitative depth estimation on CFRP samples using active thermography inspection and numerical simulation updating. NDT E Int 2017;87:119–23. https://doi.org/10.1016/j.ndteint.2017.02.003.

[8] DIKICI, B., YILMAZER, H., OZDEMIR, I., ISIK, M. The Effect of Post-Heat Treatment on Microstructure of 316L Cold-Sprayed Coatings and Their Corrosion Performance. J Therm Spray Technol 2016; 25:704–14. https://doi.org/10.1007/s11666-016-0402-z.

[9] RANJIT, S., CHUNG, Y., KIM, W. Thermal Behavior Variations in Coating Thickness Using Pulse Phase Thermography. J Korean Soc Nondestruct Test 2016; 36:259–65. https://doi.org/10.7779/JKSNT.2016.36.4.259.

[10] MALDAGUE, X., GALMICHE, F., ZIADI, A. Advances in pulsed phase thermography. Infrared Phys Technol 2002;43:175–81. https://doi.org/10.1016/S1350-4495(02)00138-X.