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# Monte-Carlo approach for fumes quantification to monitor an additive manufacturing process

Adrien Stolidi<sup>(1)</sup>, Anthony Touron<sup>(1)</sup>, Loïc Toulemonde<sup>(2)</sup> and Jean-Paul Garandet<sup>(2)</sup>

adrien.stolidi@cea.fr

(1) Université Paris-Saclay, CEA, List, Palaiseau, France

(2) Université Grenoble Alpes, CEA, Liten, Grenoble, France

Selective laser melting (SLM) is an additive manufacturing technique that uses a high-power laser to selectively fuse and solidify powdered material, layer by layer, to create complex three-dimensional objects. During the process, various parameters (type of atmosphere, laser power, lasing velocity, powder quality, ...) can induce multiple phenomena like heat transfer, fume evaporation, spatter generation or powder denudation occurring within or in the vicinity of the melt that significantly influence the fabricated part quality [1]. Indeed, considering the substantial energy densities at play, a significant concern related to the chemistry of the melt pool is that several elements may exhibit significant vapor pressures, particularly near the heat source, due to the extremely elevated temperatures reached. In alloys featuring constituents with notably distinct evaporation temperatures, it leads to observable disparities between the initial and solidified material compositions.

To highlight these effects, an *in-situ* energy dispersive X-ray fluorescence (ED-XRF) measurement of Chromium (Cr) and Nickel (Ni) content in the fumes generated during a SLM fabrication of an Inconel 625 alloy powder revealed notable fluctuations in the intensities of Cr and Ni K $\alpha$  fluorescence lines, depending on laser power, lasing speed and chamber atmosphere conditions [2]. To quantify these measurements, calibration has been carried out using Monte-Carlo particle transport simulations code PENELOPE [3]. We modeled representative setups for X-ray spectrum, flux, geometry and detector collimation. For both nitrogen (N) and helium (He) atmospheres in the SLM setup, we considered ten fixed mass fraction values for simulated Ni and Cr composition and built a calibration curve. To verify the accuracy of our quantification method, we compared the results with an analytical physico-chemical model of the melt pool, which yielded consistent findings.

[1] Ly, S., Rubenchik, A. M., Khairallah, S. A., Guss, G., & Matthews, M. J. (2017). Metal vapor micro-jet controls material redistribution in laser powder bed fusion additive manufacturing. *Scientific reports*, 7(1), 4085.

[2] Stolidi, A., Touron, A., Toulemonde, L., Paradis, H., Lapouge, P., Coste, F., & Garandet, J. P. (2023). Towards *in-situ* fumes composition monitoring during an additive manufacturing process using energy dispersive X-ray fluorescence spectrometry. *Additive Manufacturing Letters*, 6, 100153.

[3] Salvat, F., Fernández-Varea, J. M., & Sempau, J. (2008, July). PENELOPE-2008: A code system for Monte Carlo simulation of electron and photon transport. In *Workshop proceedings (Vol. 30)*. Nuclear Energy Agency, Organization for Economic Co-operation and Development, Barcelona, Spain.