Monitoring concept for powder flow monitoring in Laser-Directed Energy Deposition (L-DED) process based on flexible piezoelectric sensors [version 2; peer review: 2 approved with reservations]

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Abstract

Background: The quality of powder-blown Laser-Directed Energy Deposition (L-DED) is mainly governed by the energy density per unit of mass employed to melt the material. In most of the previous works, the focus in process monitoring and control was on the control of energy input, by controlling the properties of the melt pool. However, the powder mass input is as important to monitor as the energy input, in order to preserve the equilibrium of the process.

Methods: In this paper, the authors present the first test results of the Pyzoflex® sensor for powder flow monitoring in L-DED using real powder feeding system in the robot-based laser-processing cell. The sensor was tested against the powder projected from the powder feeder under typical flow regimes and the real-time measurements were taken using a specifically designed software tool.

Results: The graphical representation of the registered sensor signals are clearly correlated with the powder flow values set at the powder feeder, which demonstrates that the piezoelectric sensors can detect the powder flow with elevated precision in real time.

Conclusions: The first laboratory tests of flexible printed piezoelectric sensors demonstrate that they are fast and precise in the powder flow measurement, but that more effort must be invested in the robustness of the measurement setup as well as in clearing and stabilization of the registered signal.

Keywords

Additive manufacturing, powder flow measurement, monitoring systems
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Author roles: Petrovic-Filipovic V: Conceptualization, Funding Acquisition, Investigation, Methodology, Project Administration, Resources, Supervision, Validation, Writing – Original Draft Preparation, Writing – Review & Editing; Görgl R: Formal Analysis, Investigation, Methodology, Resources, Validation, Visualization; Suppan M: Conceptualization, Data Curation, Formal Analysis, Methodology, Software, Supervision, Visualization, Writing – Original Draft Preparation; Hesse J: Methodology, Resources, Supervision; Waldhauser W: Funding Acquisition, Project Administration, Resources, Supervision

Competing interests: All authors of the paper are employed at JOANNEUM RESEARCH. The piezoelectric sensors production technology presented in this study is proprietary and under related patent held by JOANNEUM RESEARCH.

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**Amendments from Version 1**

The second version of the article collects the reviewers’ comments and amends the content of the manuscript with a twofold aim: to clarify the aspects, which were found not entirely clear by the reviewers and to complement the info, which was found missing by the reviewers. In particular the conclusions have been significantly extended, improved and clarified.

Any further responses from the reviewers can be found at the end of the article.

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**Introduction**

The Directed Energy Deposition (DED) process is an additive manufacturing technique in which the powder is supplied into a focal point of a laser beam, being instantly molten and deposited over a working surface (substrate). Figure 1 shows a schematic view of the process. Argon is the vehicle for bringing the powder to the working plane. It drives the powder through a plastic tube, commonly with an internal diameter of 4mm, to the nozzle coupled with the laser head. The powder is projected from the nozzle into the focal point of the laser beam, where it is molten instantly. The laser beam melts simultaneously the substrate (creating a dilution) and the powder (cladded material), forming in this way a joint material formation. Hence, the consolidated weldseam has a strong metallurgical bond to the substrate and, if the process parameters are adequate, a 100%-density.

The processing parameters in Laser-Directed Energy Deposition (L-DED) have quite a wide range, depending on the type of material, desired productivity, available laser source, etc. but the typical value range obtained through the authors’ experience is shown in the Table 1.

In the range of laser powers stated in Table 1, even small percentages of fluctuation can cause significant energy input variation in the molten material. An insufficient energy causes bad weldseam quality, while the excessive energy causes residual thermal stresses to accumulate in the substrate. Since in Additive Manufacturing of components using DED, the substrate is actually the component itself, which grows during the build, it suffers warpage and distortion due to these residual thermal stresses. Hence, the main challenge is to keep the energy density constant at the exact (or very close) value of energy density needed to melt the supplied powder. Actually, the energy density depends on the heat input (that is, the laser power and the cross-section of the beam), but also depends on the quantity of material which is supplied into the focal point. Specifically, in powder-blown DED, this fact makes monitoring and control more complex than in other processes. As an example, in Powder Bed Fusion (PBF), the sophisticated powder distribution systems are capable of depositing smooth powder layers of down to 10µm, so the mass input is kept constant. Hence, the control of energy density is performed through the control of the energy input; mainly through the correction of laser-power to keep the melt pool size constant. However, in powder-blown DED, neither the energy nor the mass input is constant. In addition, the regulation of the powder, introduced through the nozzle to feed the additive production process, is more complex. Figure 2 shows the operating principle of a powder feeder Medicoat Duo System Integrated. The powder

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**Table 1. Typical Laser-Directed Energy Deposition (L-DED) parameters upon authors’ experience.**

<table>
<thead>
<tr>
<th>Material</th>
<th>Power [kW]</th>
<th>Speed [m/min]</th>
<th>Laser spot diameter [mm]</th>
<th>Weldseam width [mm]</th>
<th>Layer thickness [mm]</th>
<th>Overlap [%]</th>
<th>Powder mass flow [gr/min]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless steel</td>
<td>1</td>
<td>0,5-1</td>
<td>2,2-2,5</td>
<td>2</td>
<td>0,5-0,7</td>
<td>35</td>
<td>4</td>
</tr>
<tr>
<td>Titanium</td>
<td>1-3</td>
<td>0,4-3,8</td>
<td>1-4</td>
<td>2-4</td>
<td>0,5-0,9</td>
<td>35-60</td>
<td>2,9-9,4</td>
</tr>
<tr>
<td>Inconel</td>
<td>0,8-2</td>
<td>0,36-0,72</td>
<td>2-4</td>
<td>3-4</td>
<td>0,6-1</td>
<td>55</td>
<td>8-25</td>
</tr>
<tr>
<td>Stellite</td>
<td>1100</td>
<td>900</td>
<td>3</td>
<td>2,5</td>
<td>0,7</td>
<td>55</td>
<td>15</td>
</tr>
<tr>
<td>Aluminum</td>
<td>2500</td>
<td>600</td>
<td>2,5</td>
<td>?</td>
<td>1,0</td>
<td>55</td>
<td>4</td>
</tr>
<tr>
<td>Bronze</td>
<td>2200</td>
<td>480</td>
<td>3</td>
<td>2,8</td>
<td>1,2</td>
<td>45</td>
<td>6,8-10,4</td>
</tr>
</tbody>
</table>
falls from the reservoir and is pushed by the stripper into a hose that is connected with a supply of Argon, which drives the powder to the nozzle at the laser head.

The main shortcomings of the powder feeding process are the following:

- The quantity supplied by the powder feeder is not always constant – therefore, the height of the weldseam is not constant, and a variation of the stand-off distance is needed.
- There is no feedback controlling the flow rate – in standard powder feeders, the process of laser cladding is not connected to the powder feeder control, which does not allow simultaneous adjustment of laser, positioning system and powder feeding parameters.

**State of the art**

Powder flow monitoring has mostly been part of the efforts in overall process monitoring in L-DED process, as the following references show, although stand-alone works on powder flow monitoring can be found. The vast majority of the measurement techniques employed in powder flow monitoring are image-based, but we can find other concepts such as optoelectrical as well. The monitoring is based on two principles: on one hand, to measure the particles themselves (size, shape, number, density), where the image-based techniques predominate and on the other side, to measure indirectly their quantity based on the effect (optical, magnetic, etc.) they produce while they flow, where different concepts can be found.

Wu et al.\(^3\) have proposed an image-based powder measurement (IBPM) technique, based on cylindrical illumination light, used to acquire powder distribution characteristics. Instead of only monitoring the powder flow, the authors then developed a general powder distribution model of discontinuous coaxial powder stream (DCPS) based on homogeneous transformation of captured data. In similar manner, Kovacevic and his team\(^4\) tested a high-speed charge-coupled device (CCD) camera to capture the powder flow characteristics such as the particle velocity and particle distribution. Based on this data, they developed a 3D Computational Fluid Dynamics (CFD) based gas-powder flow model. Montero et al.\(^5\) also used high-speed CCD camera for a similar purpose. They used a Complementary Metal-Oxide Semiconductor (CMOS) camera (Mikrotron EOSENS) connected to a PC through a frame grabber and a 405nm, 400mW laser diode for illumination. The concept consisted of a repetitive counting of particles for a certain amount of time and weighting the powder delivered to obtain an estimation of particle weight mean and variance. They also monitored the particle density distribution. Arrizubieta et al.\(^6\) have also used a high-speed camera (without using any laser source) to measure the quantity of the powder delivered by the system, with an aperture is controlled by the solenoid valve, which position has been switched at different frequencies and the system response has been analyzed. Here, the imaging concept was used in the calibration stage of the solenoid valve voltage. This concept is especially interesting since it allows for independent closed-loop control on the top of commercial powder feeders. Smurov et al.\(^7\) used the CCD-camera based diagnostic tool for a particle-in-flight visualization, for a control of particle jet stability and for a real-time measurement of particle-in-flight velocity. The particle flux was illuminated by a continuous broadband radiation source: a high-power lamp with focusing optics to produce a spot size of about 20-mm diameter. The optical diagnostic tool consisted of a non-intensified image sensor Ex view HAD CCD manufactured by Sony Inc. with high quantum efficiency in the Near-Infrared Radiation (NIR) range and image resolution in 1038 x 1388 pixels array. Finally, based also on similar imaging techniques is the automated measuring system for powder flow analysis developed by Fraunhofer IWS\(^8\). Breese et al. investigated the powder mass flow for the LMD process, establishing a closed-loop control for a vibration feeder. A PID controller acting over a signal collected with an optical sensor was used to control a vibrational powder feeder, achieving errors of up to 9% (avg 4%)\(^9\). Finally, Osorno et al. have used a multimodal approach, with a number of sensors to monitoring not only the flow, but the melt.

**Figure 2.** Powder feeder Medicoat Duo System integrated (left), powder feeder scheme of operation (right).
pool temperature, irradiation, etc., including the commercial sensor FlowWatch establishing a fast and precise powder flow measurement\textsuperscript{10}.

From other monitoring principles, we could highlight the use of optical principle. Kovacevic’s team also used an optoelectronic sensor\textsuperscript{11}, developed to sense the powder flow rate. The authors made use of a patented powder feeder and an optoelectronic sensor, which consists of a diode laser with a line generator that emits a thin defocused light sheet with a wavelength of 658nm and power less than 500mW. It is coupled with a photo diode, a small rectangular glass chamber and a set of lenses to collimate the laser beam in the form of a line before passing through the glass chamber. Due to diffusion, absorption, and reflection of the powder stream passing through the glass chamber, the amount of light detected by the photo diode would change if the density of powder changes. The photo diode is characterized by a good linearity between the photo energy it detects and the voltage it gives out, but the authors report the existence of relevant white noise. Fraunhofer ILT has developed a method\textsuperscript{12} that allows users to calculate parameters for characterizing a powder gas jet based on the particle density distribution. The method can be used, on the one hand, to determine the position of the powder focus relative to the nozzle tip and, on the other, the diameter of the particle distribution. To use the method, the institute has developed a system based on industrial standards, one that makes it possible to carry out the measurement automatically.

In this paper, the authors present the preliminary results of testing of Pyzoflex\textsuperscript{8} sensor to measure variable powder flow. Pyzoflex\textsuperscript{8} is a flexible (both in terms of material and application flexibility) printable sensor technology, developed and owned by JOANNEUM RESEARCH that can be implemented on an industrial scale\textsuperscript{13,14}. It allows the large-scale and accurate measurement of temperature and pressure changes in objects and their environment.

In this paper, the authors tested the flexible piezoelectric sensors mainly for three reasons. The first is the because of the precision and rapid detection of measured parameters as long as the sensor is kept in operational environment below 130°C. In L-DED, the mixture of the Argon and powder has very low volumetric percentage of powder (1%) which made so far necessary to employ high-performance imaging techniques in the particle detection, with the corresponding high computation behind. The second reason is the fact that the structure of the sensor is flexible and it can be deployed on a customized measurement surface. This is important since the powder/Argon mixture is driven under pressure and, any installation of a sensor in its way, could cause a pressure drop and affect the L-DED process. Being flexible, this kind of sensor can adapt to the measurement surface or channels which cause the least pressure drop. The last reason is precisely the sensor cost. The existing attempts to measure the powder flow are based of high-cost imaging equipment, being only CMOS camera with necessary performance are above 1000\textsuperscript{15}. This contributes to the cost of L-DED equipment, which is already labelled as expensive by the industry. Deploying sensors that are cheap, flexible and have high sensibility can open the possibility of an economical breakthrough in the powder flow measurement. Unlike image-based systems, a full monitoring system with this kind of sensor (as purchased, deployed and tested in our experiments), can be set and deployed with costs under 100€.

Methods

The experimental part has been performed in JOANNEUM RESEARCH facilities in Niklasdorf, Austria. The setup is based on the use of Medicoat Duo System (more details here), which supplies the powder mixture with Argon, instead to the cladding nozzle, to the experimental breadboard shown on the Figure 3. The breadboard consisted of a printed Pyzoflex\textsuperscript{8} sensor (Figure 3, top right), which was placed into a 3D printed box (the size of the square on the paper is 5x5mm). The technology is based on sensors made of ferroelectric polymers, which are applied using a screen printing method. These films are capable of detecting localized pressure and temperature changes with high precision. The technology is named upon the pyroelectric and piezoelectric effects used for the measurement. Any mechanical deformation caused by contact, pressure/temperature changes, vibrations or shock waves is converted to a mechanical deformation (changes in thickness) and temperature differences, which on its side create electric energy. Ferroelectric polymers belonging to the PVDF-Class (polyvinylidene fluoride) are used as a basic material because they exhibit strong piezoelectric and pyroelectric activity after a poling procedure. These materials are also extremely stable, UV and weather resistant, flame-retardant and have a high chemical durability. The mixture of Argon (5l/min) and powder flow (5–30gr) (the same that is commonly provided in L-DED process) was projected onto the sensor and then, using the pyramidal design of the 3D printed housing, guided towards the outside into a deposit. The powder used was AISI 316L, with the Powder Size Distribution of 45–150µm, manufactured using the Gas Atomization process, with particles having smooth surface and perfectly spherical shape. The hot glue sealing prevented the loss of powder under Argon pressure. The Figure 3, bottom left, shows the experimental setup.

The sensor has been connected to a specially designed Printed Circuit Board (PCB), which is aimed to process and visualize the signal registered by the sensor. The main part of the electronics consists of a charge amplifier (Figure 3, bottom right) which represents a trans-impedance amplifier, but with a capacitor instead of a resistor in the feedback path. A common trans-impedance amplifier receives the input current and multiplies it by the resistance in the feedback path, which not only increases the amplitude, but also converts the current into a voltage. The charge amplifier employed here performs a similar function, but the use of capacitance instead of resistance in the feedback path creates an output that is proportional not to the instantaneous current, but rather to the accumulation of current over time. In other words, the output registers the integral of the current with respect to the time, rather than the magnitude of the current at a given moment. Therefore, the electronics transforms different impact forces, corresponding
to the different relative powder quantities in the powder-Argon mixture, into a different, measurable, voltage response. The Argon flow has been constant (5 l/min), while the powder values, provided by the powder stripper, have been ranged between 50 units (ca. 5 gr/min) and 300 units (ca. 30 gr/min).

For the data acquisition and recording of the measurement data, a custom-designed programme was developed in LabVIEW and implemented in a Vortex Microcontroller (see ‘Firmware.rar’ in Extended data). With the help of this software, the data was evaluated from the raw signals of the peak detection algorithm. For further data evaluation and to de-noise the signal, a moving average filter was implemented in LabVIEW (see ‘PiezoSoftware.llb’ in Extended data).

Procedure

More than 100 tests were made, which consisted of projection of determined quantity of powder (5l/min Argon + 5, 10, 15, 20, ... gr of steel) against the sensor, capacitance accumulation measurement data collection using a Microcortex board connected to a PC, and data interpretation using the above described home-made software tool. The measured signal is corresponding to the impact force of the projected powder, that is, to the quantity of the powder.

Since the sensibility of the sensor, necessary for real-time measurement was unknown, for different set of measurements, difference capacitors were used to find the best combination.

Therefore, in order to find the tradeoff between interval length and precision, an interplay between the size of the capacitor (3.3nF, 15nF, 22nF, 47nF, 68nF, 150nF and 470nF) and the sensor reset times (varied as 500ms, 100ms, 50ms and 25ms) was performed. The aim was to be able to detect with high precision at lowest possible interval.

Results and discussion

The graph in Figure 4 shows the generation of corresponding charge when the powder hits the Pyzoflex® transducer (see also Underlying data). The charge is repeatedly generated by the hit of an averagely constant amount of particles, which tops up the charge until the capacitor in the feedback path is fully charged. Depending on the powder concentration (quantity of powder grams in the constant 5l/min of Argon), the slope of the raw signal changes. In other words, a higher powder concentration is reflected in a higher slope, that is, a faster charging of the capacitor in the feedback path.

However, the accumulation of the charge in the capacitor is limited by its capacity. Therefore, so as to work with a single capacitor in a continuous mode, a technique of “sensor resetting” has been incorporated. It consists in the short-circuiting of the capacitor- if the capacitor is short-circuited after a determined time interval (in other words, the capacitor is discharged), it can be charged again (see Figure 5 and Underlying data). The regular charge-discharge (reset) creates
reaction time in a future closed loop control system should be as short as possible. In addition, the shorter intervals enable the accumulation of lower charge, which allows smaller capacitors to be used, which are more sensible and precise. However, the shorter intervals mean fewer points for the calculation of the slope, which has a counteracting effect on the slope calculation precision. Figure 6 shows the measurement parameters (slope and minimum analogue-to-digital converter (ADC) value) while the Figure 7 shows the representation of the slope values at different sensor reset periods and different powder flow rate values (see also Underlying data\textsuperscript{17}). Both were achieved using the capacitor of 3.3nF, which showed the best performance.

The analysis of the results show that, at higher reset intervals, the signal is more stable, which is explained by the longer slope measurement intervals which give repetitive extrapolation values. This is the case up to 200 units of powder (20gr/min). However, it must be considered that, in a closed loop control architectures, the targeted value of the system feedback and correction should be not higher than 100ms. At intervals of 100ms or lower, the stability of the signal is not as good as towards the 200ms (shorter slope intervals), although at 50 and 100ms it shows a reasonable stability. Therefore, it can be concluded that the measurement of powder flow values up to 20gr/min with reset intervals of 50–100ms show very promising results.

However, what seems to be a relevant issue is the behavior of the Pyzoflex\textsuperscript{®} sensor at values of above 200 units. At that point, a relatively strong noise and prominent peak values start to appear. After the analysis of the data, the authors conclude that the reason for this could be twofold. The first possible reason is the bouncing effect of the powder and collision with the walls of the housing, which induces additional vibrations of the sensor, not derived from the primary impact. The second possible reason is that the sensor suffers a secondary impact of powder after it is bounced back from the sensor housing walls. In other words, at

Figure 4. The cumulative charge in the capacitor at a low powder concentration (black) and the cumulative charge in the capacitor at a higher powder concentration (red). ADC, analogue-to-digital converter.

Figure 5. The sawtooth wave with regularly discharged capacitance. ADC, analogue-to-digital converter.

Figure 6. The slope is shown in red and the final (minimum) value of the charge in the capacitor is shown in blue. ADC, analogue-to-digital converter.
higher flow rates, the powder is not evacuated by the dragging Argon soon enough (probably due to a cavitation within the housing). This indicates that for higher powder flow rates than 20gr/min, a different design of the housing and outlet flow must be performed.

It must be highlighted that the sensor has not experimented any abrasion or erosion during the sensor testing, which lasted a dozen of hours. The base material used to formulate the ink for the sensor printing is a reinforced thermostable polymer, which has the operational temperature of up to 130°C, making it resistant to testing in the L-DED conditions under gases and solid particles.

**Conclusions**

In this paper, the Pyzoflex® technology has been initially tested for powder flow measurement in powder blown L-DED process. The preliminary testing results show that the monitoring of powder flow through the impact using this sensing technology is feasible and it shows the stable and precise measurement when employed for the values of up to 20 gr/min of powder. However, for the use above this value, it is needed to continue working on the experimental setup, looking for targeted housing design that can eliminate noise and secondary charge generation at higher powder flow rates.

The first item in the follow-up work will be the design of a housing for the sensor. The present design provokes a bouncing-back effect, which can create a noise in the measurement. However, this work aimed to demonstrate the sensitivity and viability of the concept at the lab level, not in the real process. The definite version of the housing will have a design that allows smooth evacuation of the gas-powder mixture towards the process plane without pressure loss. This will be enabled by the capacity of the Pyzoflex technology to print sensors on freeform surfaces, including concave planes, for example. Therefore, the noise in the measurement will be fully avoided by the new housing design, free of geometry constraints.

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**Figure 7.** The representation of the slope at 50, 100 and 200 units of powder feeder (5.5, 11, 22 and 33 gr/min, respectively), using the automatic sensor reset time of 500ms (up left), 100ms (up right), 50ms (down left) and 25ms (down right).
The minimum resolution of the sensor was 0.1 gr/min – the authors believe that the precision can go down to the 0.05 gr/min, but this has not been confirmed, since the precision of the digital setup (software for registration of the ADC values and their conversion to the gr/min) was 0.1 gr/min. Also for our application of cladding, the precision of 0.1 gr/min is sufficient, which is why we have set that goal. As a part of the future work, it is envisaged to improve the software precision, thus, the measurement precision for the reasons explained in the Answer A6.

In addition, the range of measurement values this time was between 5 and 30 gr/min, which are the typical values of the cladding process performed at JOANNEUM RESEARCH (the range of beam spots we use in our processes is 1–2.5mm). Therefore, for the values below 5gr/min, the sensor was not tested and it remains as a future work.

Last but not the least, at JOANNEUM RESEARCH there are no commercial solutions such as FlowWatch® or similar. Actually, the idea in the project, in which this work was funded, was to create a low-cost R&D-oriented solution for powder flow monitoring. Therefore, the comparison of the piezoelectric monitoring concept with commercial solutions has not been performed. Yet, in parallel, the authors have developed a robust light-scattering based powder flow monitoring principle, based on the combined use of laser light (emitter of the laser light) and an avalanche photodiode (receiver of the laser light signal diminished by the scattered light). The testing results of this optical concept were compared internally with the piezoelectric monitoring concept presented in this paper. Although the measurement data about the light-scattering concept are not the matter of this paper and will be published separately, we can state that the piezoelectric monitoring concept is characterized by a higher sensitivity and higher precision, but the light-scattering principle offers more robustness and less noise in the measurement. Therefore, our future work related to the piezoelectric monitoring concept will be focused on the application fields with higher precision requirements, including microcladding or plasma coating.

Data availability
Underlying data
Dryad: Pyzoflex technology testing for powder flow monitoring. https://doi.org/10.5061/dryad.3xsj3txhs17.

This project contains the following underlying data:
- Figure 4_THE_CUMULATIVE_CHARGE.csv
- Figure 5_THE_SAWTOOTH_WAVE.csv
- Figure 6_THE_SLOPE.csv
- Figure 7_THE_REPRESENTATION_OF_THE_SLOPE_Down-Left-50ms.csv
- Figure 7_THE_REPRESENTATION_OF_THE_SLOPE_Down-Right-25ms.csv
- Figure 7_THE_REPRESENTATION_OF_THE_SLOPE_UP-LEFT-500ms.csv
- Figure 7_THE_REPRESENTATION_OF_THE_SLOPE_UP-Right-100ms.csv
- README.txt (provides an overview of the data contained in each file).

Data are available under the terms of the Creative Commons Zero “No rights reserved” data waiver (CC0 1.0 Public domain dedication).

Extended data
Archived analysis code at time of publication: https://doi.org/10.5281/zenodo.62200316

License: MIT

References


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The research article reviewed deals with the development of a piezoelectric sensor for powder flow measurement in the directed energy deposition laser beam process with powder as feedstock (DED-LB/p) also known as Laser Metal Deposition (LMD) process. The article fits well in Materials Open Research Journal scope, because the research is original, innovative and of high interest for the LMD process monitoring to support process development and process quality assurance in laser material processing of metals using powder as feedstock, in particular, in laser cladding for coatings and for medium to high size components in additive manufacturing applications.

The introduction section is well oriented, but the state-of-the-art lacks recent references and literature related to powder flow monitoring solutions for LMD using optical powder flow sensors already available in the market (like Medicoat FlowWatch). Here, I recommend to analyze the following research papers: Breese et al. (2021), Müller et al. (2023) and Osorno et al. (2021). This research study brings interesting preliminary results, but the redesign of the sensor housing and the validation of preliminary results need a more elaborated work to be conclusive.

My main comments and suggestions are the following:
1. What anomalies in the powder flow can cause the impact of gas and particles flow on the Pyzoflex sensor?

2. Since the sensor operation mode is the hitting of powder particles, has the durability of the Pyzoflex sensor material to abrasion and erosion of metallic particles been evaluated in any way?

3. In the housing, are powder particles accumulating in those confined areas where turbulence and gas flow conditions are not adequate? Was this aspect evaluated and inspected?
4. In the research paper it is stated that a certain amount (in grams) of steel was used for trials and testing, but could you please detail in terms of powder particles used (and since this is a Materials and Processes journal) what specific type of alloy, particle size, morphology, apparent density, and chemical composition was ultimately used?

5. Has the minimum reading resolution of the sensor been analyzed? Can it work from 0.5 g/min or lower for example? This question is of utmost interest for mixing of powder in the creation of new alloys or in FGMs.

6. Has a benchmark been made with the response and sensing capacity and accuracy of this solution and commercially available optical or capacitive sensors? It would be of great interest to the scientific community from the point of view of process monitoring and potential process control strategies.

7. The conclusions drawn are brief and tentative; perhaps there are more results and conclusions that could be added after a simple verification of the tests analyzed and their validation.

References

Is the work clearly and accurately presented and does it engage with the current literature?  
Partly

Is the study design appropriate and does the work have academic merit?  
Yes

Are sufficient details of methods and analysis provided to allow replication by others?  
Yes

If applicable, is the statistical analysis and its interpretation appropriate?  
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?  
Partly

Are the conclusions drawn adequately supported by the results?  
Partly
**Competing Interests:** No competing interests were disclosed.

**Reviewer Expertise:** Laser cladding; Laser Metal Deposition; Selective Laser Melting; Laser Welding; Laser based additive manufacturing

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

**Reviewer Report 08 September 2022**

https://doi.org/10.21956/materialsopenres.18702.r26811

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The paper “Monitoring concept for powder flow monitoring in Laser- Directed Energy Deposition (L-DED) process based on flexible piezoelectric sensors” by Petrovic-Filipovic et al. deals with the control of the powder flow in LDED. The authors have used a piezoelectric system to demonstrate the possibility of monitoring the powder flow supplied by a powder system used in LDED (or laser cladding)

The results are in the scope of Materials Open Research journal. These can be useful, but I find some points to be addressed:

**General comments:**
This work is interesting and very comprehensive. It deals with a relevant topic; however, after reading the paper I have some general comments:
1. This work deals with a relevant topic, the monitoring of the powder flow in LDED or laser cladding. As pointed out by the authors, the monitoring of the powder flow is key in LDED or laser cladding (not considered by the authors). This approach is interesting, however, it is not clear how this approach can help to monitor the powder flow during LDED. This can be a solution to make a calibration of a powder feeding system, but seems not suitable to control the powder flow during the process. The authors should clarify this point as it is the main aim of the paper.

2. Notice that this system could have utility in LDED but also in laser cladding (not considered in the manuscript).

**Particular comments:**
1. (Introduction) Please, add the particle diameter range for the materials considered in Table...
1. (State of the art) Please, replace “The first is the because of the precision and rapid detection of measured parameters as long as the sensor is kept in operational environment below 130°C.” with “The first is a consequence of the precision and rapid detection of measured parameters as long as the sensor is kept in operational environment below 130°C.”

2. (Methods) Please, in “based on the use of Medicoat Duo System (more details here)” add a reference rather than a link.

3. (Methods) Please, provide more details/characteristics of the PCB to make the system reproducible.

Is the work clearly and accurately presented and does it engage with the current literature?
Yes

Is the study design appropriate and does the work have academic merit?
Partly

Are sufficient details of methods and analysis provided to allow replication by others?
Partly

If applicable, is the statistical analysis and its interpretation appropriate?
Not applicable

Are all the source data underlying the results available to ensure full reproducibility?
Partly

Are the conclusions drawn adequately supported by the results?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Laser materials processing, laser cladding, additive manufacturing, laser surface engineering, bioactive glasses, nanoparticles, nanomaterials

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 13 Sep 2022
Vojislav Petrovic-Filipovic

Dear Mr. Riveiro, In the first place, many thanks for your comprehensive review. Secondly, I would like to address your major comments:
1. The term Directed Energy Deposition (DED), according to the ASTM F3187-16 "Standard Guide for Directed Energy Deposition of Metals" is used to determine "an additive manufacturing process in which focused thermal energy [in this case, laser energy] is used to fuse material by melting as they are being deposited". To the authors' understanding, L-DED is a physical process, while laser cladding, laser repair or generative manufacturing of 3D part are production techniques which use the L-DED process to different aims - in the case of laser cladding, for surface coating. Therefore, we consider that by referring to "L-DED" in the manuscript, we cover all these application casuistries.

2. The development of a monitoring concept, in our opinion, has two aims: monitoring and closed-loop control. The monitoring can be applied to any of the existing powder feeders, since it doesn't interact with the powder feeder's control unit. The monitoring doesn't prevent possible defects caused by the variation of the powder flow, but it does register the "event" and warns that in determined point of the deposited material there might be an error. A closed-loop control, as you rightly point out, is not possible with present commercial powder feeders, but the authors are developing a small experimental powder feeder with closed loop control within the funded project stated in the "Grant information" section. We didn't discuss this in the manuscript, since we aimed to focus on the evaluation of the sensor only. However, we can gladly add this information.

**Competing Interests:** No competing interests were disclosed.