Machine-dynamics monitoring for L-DED operations

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Abstract: Laser Directed Energy Deposition is an Additive Manufacturing technology that enables repairing or coating high-added-value components. The obtained results depend on the process parameters, but also on the machine dynamics, e.g. the capability of the machine to follow the programmed trajectory at a constant velocity. In the present research work, the response of a laser machine and a FAGOR 8070 CNC control at different situations is analysed. Special attention is paid to the trajectory smoothing command of the control. The machine acceleration is found to affect the initial and final accelerations, but not the velocity reduction in the direction change. On the contrary, the value of the chordal error influences the machine deceleration in the direction change corner, whereas its influence is almost negligible in the initial and final accelerations.

Keywords: Additive Manufacturing, Monitoring, On-machine measurement, Dynamics.

1. Introduction

Directed Energy Deposition (DED) is an Additive Manufacturing (AM) technology based on the injection of filler material, while it is simultaneously melted by a heat source. The heat source generates a melt pool on the substrate, where the material is being deposited and typically a protective atmosphere is required to avoid material oxidation. Thanks to the repeated deposition operation, successive layers are overlapped until the desired geometry is obtained [1].

Nowadays, there are various configurations of DED processes available: Powder-based Laser-DED (L-DED), Wire-based L-DED, Wire Arc Additive Manufacturing (WAAM), and Kinetic Energy-based DED. Powder-based L-DED systems have been studied in-depth in both the literature and the industry, and it is considered the most common metal DED process [2]. Therefore, the present study will focus on this process, despite it could be directly extended to any other DED process.

The obtained results in powder L-DED are highly dependent on the process parameters [3], being the main ones the laser power, the laser beam spot size, the powder mass flow, and the machine feed rate. However, besides optimizing them, it is mandatory to keep their values as constant as possible to avoid process instabilities. Online monitoring systems have been developed to maintain a constant process temperature or melt pool size based on regulating the laser power [4]. Also, some attempts to control the powder feed rate in real-time have been carried out [5]. Nevertheless, process velocity is found to be a key parameter when ensuring process stability.

The tool path problem has been extensively studied to reduce non-productive times and to increase the process productivity [6], however, in L-DED, this issue is much more complex than in conventional manufacturing processes (e.g. machining). The tool path influences the geometry, properties, and quality...
of the final part, even when using the same DED machine and the same process parameters [7]. If the velocity of the L-DED head varies from the programmed feed rate, so does the interaction time between the laser and a certain point of the surface of the substrate. Therefore, the irradiated laser energy and the amount of injected filler material per unit length also change. Consequently, trajectory smoothing algorithms need to be implemented to ensure a constant velocity.

Trajectory smoothing can be obtained either locally or globally. Local algorithms assume that the linear segments are sufficiently long to avoid interferences between consecutive corners. On the contrary, global smoothing algorithms are focused on short segments. However, the actual CAM outputs are typically combinations of continuous segments of different lengths. Thus, neither the local smoothing algorithm nor the global smoothing algorithm can adequately handle these combinations of different length segments. To solve this issue, Bingran et al. proposed a neural network control algorithm [8].

On the other hand, Xie et al. proposed an optimized tool path, which increases the process productivity by minimizing the processing time [9]. Similarly, Tajima et al. [10] generated a tool path by directly planning jerk-limited velocity transitions near sharp corners, while Duan et al. [11] used optimal control to realise minimum-time cornering. Nevertheless, in L-DED ensuring a constant velocity is as important as the process productivity itself.

Comminal et al. investigated the effect of smoothing the toolpath of the corners for 90º and 30º turns. A uniform strand width was obtained when the extrusion rate was kept proportional to the feed rate [12]. Nevertheless, the algorithm was implemented for the extrusion AM process, Fused Deposition Modeling (FDM), where there is no laser beam and the material is injected in wire form, whereas in L-DED there is no possibility to instantaneously control the mass flow rate while keeping it proportional to the machine real velocity.

This fact is more accentuated when complex trajectories are followed, such as 5-axis L-DED. Plakhotnik et al. proposed a new approach for toolpath generation for DED, where the laser orientation was optimized to ensure a more constant linear velocity of the laser beam on the surface of the substrate [13]. Nevertheless, resulting velocities were not monitored during the DED process.

In order to overcome this lack in the literature, the present work, studies the behaviour of an L-DED head, when trajectories with different angularities are described. Velocity and position errors are monitored during the process and the smoothing capability of the G501 command from the FAGOR 8070 CNC is evaluated for various machine feed rates, corner angles, chordal errors, and acceleration combinations.

2. Used equipment and methodology

Experimental tests have been carried out in a 5-axis laser centre, the Kondia Aktinos 500, despite in the present study only the three linear axes have been employed. The X and Y linear movements are given by the working table, while the Z movement is given by the L-DED head.

The machine position is controlled by a Fagor 8070 CNC control, which includes a trajectory smoothing algorithm. This smoothing algorithm is activated by the G501 code, followed by the machine acceleration as a percentage of the reference value, the chordal error, and other parameters such as the percentage of jerk value. This command was developed mainly for milling operations in the mould-making sector, and in the present case, its validity for the L-DED process is studied.

Four sets of tests have been carried out to analyse the influence of the machine feed rate, \( F \), the trajectory angularity, \( \theta \), the machine acceleration, \( A \), and the chordal error, \( E \), of the CNC. In each set, the parameter to be studied is varied, whereas the rest are kept constant. The tests consist of two straight lines, with a variable direction-change angle between them, which obliges the machine to work under different dynamic loads. The chordal error and the trajectory angularity are defined according to figure 1.
Figure 1. Examples of (a) low angularity and (b) high angularity trajectories at point “N”. In both cases, the chordal error is highlighted.

Experimental data is obtained directly from the CNC control by means of the oscilloscope mode, which allows monitoring the desired variables in real-time. Numerical values of the monitored parameters are saved every 4 ms, which is the minimum acquisition time interval. Afterwards, they are extracted in .txt format for their subsequent analysis. In the present case, the X and Y positions of the L-DED head and the real velocity and accelerations have been monitored, which are compared with the programmed target values.

3. Results

The results are presented in three different blocks, which correspond to the influence of the trajectory angle and machine feed rate variations, the machine acceleration, and the chordal error. In each test block the input parameters that are not being studied are kept constant and at their reference values: 750 mm·min⁻¹ feed rate, 100% acceleration, and 0.15 mm maximum chordal error.

3.1. Influence of the trajectory changes and machine feed rate

In L-DED operations, typical machine feed rates around 750 mm·min⁻¹ are employed, and therefore, in the present study feed rates ranging 500 and 1000 mm·min⁻¹ are studied. In figure 2 the velocity of the laser head is plotted, while the programmed trajectory is followed at a 500 mm·min⁻¹ feed rate. In the straight regions, the machine velocity is the same in all cases and equal to the programmed feed rate. But, if the trajectory-change region is analysed in-depth, differences are encountered depending on the programmed angle, named as “Theta” in figure 2. This same tendency has been noticed in the case of 750 and 1000 mm·min⁻¹ feed rates, but in those cases, as is detailed in Table 1, the velocity reduction is more pronounced as the feed rate increases. Note that in all these tests the G501 smoothing algorithm has been activated with a 0.15 mm chordal error value and the maximum machine acceleration was not limited.

Due to the asymmetric nature of the machine, where the X and Y movements of the table are not symmetrical, the acceleration in the X and Y axes is not the same. In the present case, a slightly lower acceleration is detected in the X-axis, which is the longest. This is the reason why the highest velocity reduction is obtained for the 150° angle.

In table 1, the velocity reduction in the direction change region is quantified. In order to provide comparable values, in all cases, the velocity reduction is calculated as a percentage of the feed rate. The monitored velocity reduction increases with the angle of the trajectory, reaching almost zero velocity values for angles over 150°. As can be seen in table 1, the velocity reduction of the L-DED head is inversely proportional to the machine feed rate and increases with the sharpness of the direction change angle.
Figure 2. Velocity of the L-DED head at a 500 mm·min\(^{-1}\) feed rate, a 0.15 chordal error, and a 100% machine acceleration.

Table 1. Velocity reduction in the direction change as a percentage of the nominal value.

| \(\theta\) [°] | Feed rate          |
|--------------|--------------------|
|              | 500 mm·min\(^{-1}\) | 750 mm·min\(^{-1}\) | 1000 mm·min\(^{-1}\) |
| 0            | 0.03               | 0.03                 | 0.03                   |
| 30           | 1.15               | 1.55                 | 1.96                   |
| 60           | 7.07               | 10.24                | 11.97                  |
| 90           | 19.96              | 27.95                | 45.24                  |
| 120          | 38.61              | 63.45                | 72.62                  |
| 150          | 93.10              | 95.20                | 96.89                  |
| 180          | 89.13              | 93.55                | 96.25                  |

Therefore, it can be concluded that the velocity reduction in direction change regions becomes more problematic as the nominal feed rate of the machine is increased and when trajectories with sharp angles are programmed.

Figure 3. Velocity of the L-DED head for a 750 mm·min\(^{-1}\) feed rate, 90° direction change, and various machine accelerations, as well as a detail of the direction change region.

3.2. *Influence of the machine acceleration*

The acceleration of the machine can be limited by applying a percentage of the nominal acceleration
value in the trajectory smoothing command. As concluded in the previous section, the trajectory sharpness strongly influences the velocity reduction of the L-DED head, but their relation is proportional. Thus, an average value of 90° of the trajectory angle is considered for the study of the machine acceleration, as well as a constant 0.15 mm maximum chordal error. Machine feed rates of 500, 750, and 1000 mm·min⁻¹ have been studied. In figure 3 the values of the measured velocity of the L-DED head for the reference feed rate of 750 mm·min⁻¹ is shown, but the same dynamic behaviour of the machine is detected along all the studied feed rates. Contrary to what was expected, it is proven that the acceleration parameter does not affect the dynamics of the machine in the direction change corner and the velocity reduction in the direction change depends only in the nominal feed rate and the trajectory angle. On the other hand, the acceleration command influences only the beginning and the end of the track, whereas its influence in the direction change is minimal and can be neglected.

With regard to process dynamics at the beginning of the clad, the amount of time required for achieving the programmed velocity value has been quantified. In Figure 4, the variation of the velocities and accelerations for the different studied cases is shown, whereas the exact values are provided in table 2. Higher accelerations lead to shorter transient times and, for accelerations above 60% of the nominal value, i.e., accelerations of more than 216 mm·s⁻², this time is reduced to approximately less than 0.1 s for the 750 mm·min⁻¹ feed rate.

In all cases, a sawtooth-type movement has been detected in the acceleration signals at the beginning of the clad, which is a consequence of the machine startup. Therefore, these signal variations have been neglected in the afterward analysis for the maximum acceleration value determination.

![Initial velocity](image1)

**Figure 4.** Details of the initial velocities and accelerations of the L-DED head for a 750 mm·min⁻¹ feed rate and various machine accelerations.

**Table 2.** Analysis of the initial machine acceleration, where the reached maximum acceleration and the time to reach a stable velocity are detailed.

| Test Nr. | % Acceleration | Reached Maximum acceleration [m·s⁻²] | 500 mm·min⁻¹ | 750 mm·min⁻¹ | 1000 mm·min⁻¹ | Time to reach a stable velocity [s] |
|----------|----------------|--------------------------------------|--------------|--------------|--------------|------------------------------------|
| A100     | 100            | 362.5                                | 0.072        | 0.088        | 0.088        |                                    |
| A80      | 80             | 331.25                               | 0.088        | 0.100        | 0.104        |                                    |
| A60      | 60             | 268.75                               | 0.096        | 0.108        | 0.120        |                                    |
| A40      | 40             | 212.5                                | 0.104        | 0.124        | 0.152        |                                    |
| A20      | 20             | 131.25                               | 0.136        | 0.192        | 0.232        |                                    |
| A10      | 10             | 87.5                                 | 0.232        | 0.304        | 0.376        |                                    |
| A1       | 1              | 62.5                                 | 1.704        | 2.532        | 3.841        |                                    |

For angles other than 90°, the velocity reduction in the direction change will vary as detailed in Table 1; but the reduction remains constant independently of the acceleration value defined in the trajectory smoothing algorithm.
3.3. Influence of the chordal error

Finally, the influence of the maximum allowed chordal error on the L-DED head trajectory is analysed under the situation of a constant value of the direction change angle of 90º, a 750 mm·min⁻¹ feed rate (which are the average values of the process parameters tested in previous sections), and a 100% acceleration (which means that the maximum acceleration is not limited).

As it is shown in figure 5, the initial acceleration of the machine is the same in all situations analysed, and therefore, so is the measured velocity signal at the beginning of each test. However, differences have been encountered in the direction change region. As expected, higher chordal errors have led to lower velocity reductions. For a maximum chordal error value of 0.25 mm, the monitored velocity signal is almost constant, and reductions of only 18% have been measured when compared to the programmed feed rate.

![Figure 5. Velocity of the L-DED head for a 750 mm·min⁻¹ feed rate, 90º direction change, and various chordal errors, where details of the initial and direction change region are provided.](image)

| E [mm] | Velocity reduction [%] |
|--------|------------------------|
| 0.001  | 96.44                  |
| 0.05   | 90.55                  |
| 0.1    | 93.12                  |
| 0.15   | 27.95                  |
| 0.2    | 21.47                  |
| 0.25   | 18.08                  |

After evaluating all the results, which are detailed in table 3, a threshold value of the chordal error has been defined. Values above 0.15 mm present almost no velocity reduction, whereas chordal errors below that value produce considerable velocity errors.
Figure 6. Analysis of the L-DED head position in a 90° direction change angle for a 750 mm·min⁻¹ velocity and an increasing chordal error.

Regarding the precision of the trajectory, in figure 6, the different paths followed by the L-DED head are compared. For the highest chordal error, the machine produces a considerable tracking error, which depending on the application may lead to unacceptable geometrical errors. Therefore, considering both the trajectory precision and the velocity reduction factor, 0.15 mm is considered to be the best chordal error value.

4. Conclusions

Unlike in subtractive manufacturing processes such as machining, where the accuracy of the operation is quantified based on the tool's ability to accurately follow the programmed path; in L-DED, achieving a stable process is essential. This is due to the fact that, in L-DED the injected mass rate of the filler material is constant during the deposition process, and since the height of the deposited clad depends on the amount of material injected per unit length, which is inversely proportional to the real velocity of the machine, any variation in the L-DED head velocity results in deviations in the deposited clad height.

Hereafter, the main conclusions reached after the present study are detailed:

In order to obtain homogeneous speeds, it is recommended to reduce the angle of the direction changes in the tool path trajectories. For the velocity range studied, it is desirable that the trajectory does not have an angularity of more than 60° to avoid velocity reductions over 10%. Therefore, the first step is to smooth the trajectories to be followed by the L-DED head. If the tool path cannot be smoothed directly in the CAM software employed to generate the trajectories, it would be necessary to apply smoothing strategies such as FAGOR's G501, which has been studied in this work, directly in the L-DED machine.

After the present analysis, and considering the employed setup, it is confirmed that a maximum chordal error value of 0.15 mm provides a relatively homogeneous speed, together with a minimum tracking error, establishing this value as the most appropriate as it provides a good settlement solution.

Increasing the machine's feed rate is counterproductive in terms of the accuracy of the machine's forward motion, and changes in the deposition direction at higher machine feed rates result in greater decelerations, both in absolute and relative values. Therefore, from a process stability point of view, it is advisable to add material at low feed rates. On the contrary, high feed rates are only recommended when no direction changes are expected, i.e. coating of revolving parts, where there are no changes in the deposition direction.

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References

[1] Cooke S, Ahmadi K, Willerth S and Herring R 2020 Metal additive manufacturing: Technology, metallurgy and modelling Journal of Manufacturing Processes 57 pp 978–1003

[2] Dass A and Moridi A 2019 State of the Art in Directed Energy Deposition: From Additive Manufacturing to Materials Design Coatings 9 p 418

[3] Moradi M, Ashoori A, Hasani A 2020 Additive manufacturing of stellite 6 superalloy by direct laser metal deposition – Part 1: Effects of laser power and focal plane position Optics & Laser Technology 131 p 106328

[4] Xia C, Pan Z, Polden J, Li H, Xu Y, Chen S, Zhang Y 2020 A review on wire arc additive manufacturing: Monitoring, control and a framework of automated system Journal of Manufacturing Systems 57 pp 31-45

[5] Arrizubieta J I, Martinez S, Lamikiz A, Ukar E, Arntz K, Klocke F 2017 Instantaneous powder flux regulation system for Laser Metal Deposition Journal of Manufacturing Processes 29 pp 242-251

[6] Murua M, Suárez A, Galar D and Santana R 2020 Tool-path problem in direct energy deposition metal-additive manufacturing: sequence strategy generation IEEE Access 8 pp 91574–91585

[7] Jiang J and Ma Y 2020 Path Planning Strategies to Optimize Accuracy, Quality, Build Time and Material Use in Additive Manufacturing Micromachines 11 p 633

[8] Bingran L, Hui Z, Peiquing Y, Jinsong W 2020 Trajectory smoothing method using reinforcement learning Robotics and Computer Integrated Manufacturing 61 p 101847

[9] Xie F, Chen L, Li Z, Tang K 2020 Path smoothing and feed rate planning for robotic curved layer additive manufacturing Robotics and Computer Integrated Manufacturing 65 p 101967

[10] Tajima S and Sencer B 2016 Kinematic corner smoothing for high speed machine tools International Journal of Machine Tools and Manufacture 108 pp 27-43

[11] Duan M and Okwudire C 2016 Minimum-time cornering for CNC machines using an optimal control method with NURBS parameterization International Journal of Advanced Manufacturing Technologies 85 pp 1405–1418

[12] Comminal R, Serdeczny M P, Pedersen D B, Spangenberg J Motion planning and numerical simulation of material deposition at corners in extrusion additive manufacturing Additive Manufacturing 29 p 100753

[13] Plakhotnik D, Glasmacher L, Vaneker T, Smetanin Y, Stautner M, Murtezaoglu Y, Houten F 2019 CAM planning for multi-axis laser additive manufacturing considering collisions CIRP Annals - Manufacturing Technology 68 pp 447–450