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CAM planning for multi-axis laser additive manufacturing considering collisions

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ABSTRACT

In this paper, the presented approach resolves important aspects that appear in the process planning for multi-axis Direct Laser Additive Manufacturing: smoothing of the nozzle orientation along the toolpath to reduce deviation of the laser spot's surface speed, redistribution of the toolpath points on the surface to ensure robust processing of the points by the machine tool, collision avoidance between the nozzle and the workpiece by adjustment of the nozzle orientation. Collision avoidance penalizes the lateral tilting to minimize the change of the laser spot size due to tilting and, therefore, it has reduced its impact on the process.

1. Introduction

Additive manufacturing has been used for fabricating three-dimensional metallic components since more than a decade. From its inception, this fabrication method relies heavily on the laser as the energy source to melt the deposited material. Additive manufacturing at its very beginning promised seamless production of complicated shapes without the need of complicated tooling in a simple layer-by-layer material deposition.

As the application scope of additive manufacturing has broadened to the repair of, for example, dies, molds, and turbine blades, it became obvious that the initial layer-by-layer approach cannot build up on curved surfaces. Besides, the need of support structures and subsequent support removal has significantly reduced the attractiveness of the laser additive manufacturing (LAM), especially Directed Energy Deposition (DED), as it limits the design freedom, increases time and cost of production and reduces the quality of the surface of the printed product.

In order to overcome different limitations and inefficiencies of the classical layered approach, multi-axis positioning of the depositing device has been introduced. Additional rotational degrees of freedom allowed switching from flat layers to curved slices. Initially, only simple geometries have been considered in DED. As an example of such early developments, a solid metal hemisphere was fabricated using 5-axis powder deposition [1]. The laser toolpath was just a helical path that followed the surface of the hemisphere. Due to the simplicity of the shape, CAM planning was straightforward and did not encountered issues typical for free-form surfaces, like considering step-over distances between adjacent toolpaths or potential collision.

Multi-axis LAM extends beyond the classic deposition in a layer-by-layer manner. CAM planning for such multi-axis operations is non-trivial because of several issues, that are specific for multi-axis approach: smoothing of tool orientation change and collision control.

Most of toolpath generation strategies results in toolpaths with abrupt changes in the move directions. Due to limited jerk of the machine, sharp corners are likely to lead to slow down of the machine, thus causing overexposure to the laser and with that result in, for example, local variations in mechanical properties and surface characteristics [2]. Minimization and smoothing of end-effector rotations for multi-axis operations can be resolved by using graphs and dynamic programming [3–6].

The problem of collisions between the spindle and workpiece during five-axis machining has already been addressed in industrial CAM software and academic research [7]. However, there is a principal difference in avoiding collisions in five-axis milling and LAM. In ball-end milling, the spherical end of the milling cutter cuts material and generates the machining strip. Because the contact zone between the tool sphere and the workpiece remains constant regardless the tool orientation, the machining strip width is not influenced by the orientation of the milling tool. But this rule does not apply on DED, because the size and configuration of the laser spot changes if the laser beam is not positioned normal to the surface. The state-of-the-art approach is to define the laser orientation to be normal to the surface [8]. However, this strategy is ill-defined for following free-form surface, especially if collision obstacles make it infeasible to preserve the normal orientation. Therefore, the existing methods imply layer scheduling to prevent collisions [9,10] without speculating about changing the tool orientation.

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In this paper, we describe a new approach for toolpath generation for DED. In contrast to toolpath planning in traditional five-axis milling, the developed approach penalizes selection of laser orientations that tilt aside from the feed direction in order to reduce variation of the laser spot shape on the surface. Additionally, the laser orientation is optimized for smooth change and more constant linear velocity of the laser spot on the surface, while ensuring a full collision control between the laser head and stock. The laser head is modeled as a mesh, and it is used in the computation routine for finding collision-free postures.

2. Methodology

In this paper, mainly applications like repair or rebuilding of part features in pre-machined metal forms (e.g. a forming die, broken impeller blades) are addressed, since such applications have especially challenging collision conditions that can be efficiently resolved by applying multi-axis strategies.

Technically, the workflow starts from obtaining the geometries of the existing part, usually scanned data, and design volume to be produced. Then, the base surface is offset to generate 3d layers. Each 3D layer is used to generate equidistant, also known as geodesic, toolpaths.

2.1. Redistribution of toolpath points and initialization of a collision-free toolpath

For high quality DED processes the energy input (per time interval) on the surface is required to stay constant. Change in spot size (&shape) and spot size travel speed are the main reasons for variations in this energy input. Traditional toolpath generation algorithms only must take collision detection into account and assign key points based on this collision detection. The method described below adds additional sample points to be able to optimize laser orientation between key points. However, in many cases, preserving the orthogonal orientation may be either inefficient due to substantial orientation changes or even impossible due to collision obstacles.

Toolpaths for DED applications may consist of millions of points. Finding smooth and collision-free tool orientations in a brute-force manner is almost surely to take too long time. Time to find proper tool orientations can be shortened by precomputing of tool orientations at so-called key points. The key points are the points at which the toolpath changes significantly its direction or curvature. If the distance between two neighbor key points exceeds a given threshold, additional key points will be inserted, as shown in Fig. 1.

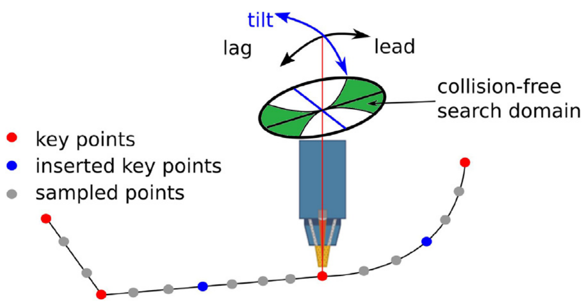


Fig. 1. Initialization of key point and initial orientation.

Collision-free tool orientations at key points are computed. If there is a collision of the tool when normal to the surface, the lead/lag angles are incremented by 1–3° until collision is avoided. If collision cannot be avoided, the search continues in the collision-free search domain (with side tilt). This strategy is chosen based on the assumption that the laser spot can be either a circle or ellipse, as shown in Fig. 2. In general, “stay normal to surface” should result in a circle spot, otherwise the spot will be deformed. In case tool orientation changes are needed, tilting in feed direction is

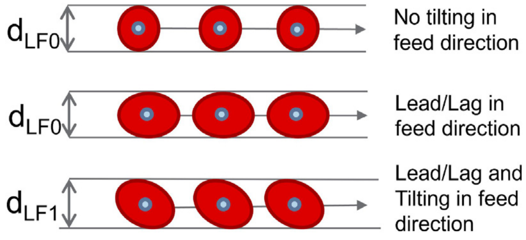


Fig. 2. Laser spot shape and dimensions depending on whether lead/lag and tilt are applied.

preferred, as it does not alter the width (d_{LF1}) in relation to the intended/original laser width (d_{LF0}).

Depending on the sampling distance parameter, the number of sampling points (points between key points) on the toolpath changes. Large number of sampling points will impact the calculation speed significantly, at the same time the difference in quality might not be critical. The orientations at sampling points are interpolated with SLERP interpolation, as demonstrated in Eq. (1). SLERP interpolation is a spherical interpolation of constant-speed motion of a vector along a great circle arc, given the ends and an interpolation parameter between 0 and 1. The distance between two key points is parametrized to [0 . . . 1], and each sampling point has a coordinate t within this interval.

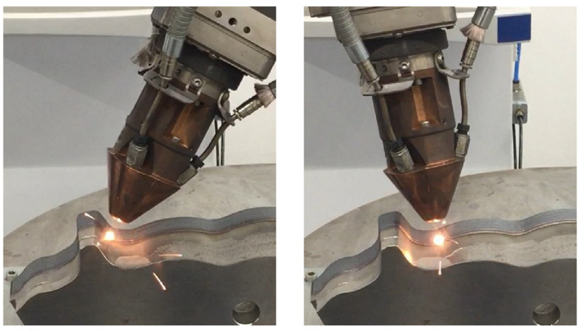
$$\mathrm{Slerp}(\mathrm{v}_0;\mathrm{v}_1;\mathrm{t}) = \sin\frac{[(1-t)\theta]}{\sin\theta}\mathrm{v}_0 + \sin\frac{[t\theta]}{\sin\theta}\mathrm{v}_1 \quad (1)$$

where $\mathbf{v_0}$ and $\mathbf{v_1}$ are the orientations at first and second key points; t is the interpolation parameter of a sampling point; θ is the angle between $\mathbf{v_0}$ and $\mathbf{v_1}$;

In most of the cases, all interpolated positions between two key points are also collision-free. However, there is a chance that a collision may still happen. Therefore, the orientations at sampling points are to be checked against collisions, and new feasible orientation is resolved, if needed. Every reorientation initiates SLERP reinterpolation of orientations at all sampling points, such as if the reoriented sampling point acted as a key point. This procedure may run iteratively adjusting orientations at sampling points, until all positions satisfy collision conditions. Tool positions will be checked for collisions every 3° (angle step of the tool axis). If there are portions along the contour on which the tool is very close to the geometry, then a 3-degree step might be too rough to find an optimal collision-free orientation, and the step must be decreased.

2.2. Toolpath smoothing

In case of significant changes of tool orientation, as shown in Fig. 3, the nozzle slows down due to the jerk limits of rotary axes. Hence, the surface is overexposed to the deposition during the move. In order to prevent such cases and smooth the orientation changes, the orientation vectors are not allowed to have an angle change between sampling points more than a specified value, usually 3° is enough for generic cases.



a) first position **b)** second position

Fig. 3. Significant orientation change during a move.

Smoothing reduces the angle change between tool orientations. It is applied not globally, but on groups of sampling points. There are several runs of smoothing. Every run, group length increases from one to several (3–5) look-ahead distances, which is defined by a user and should cover several sampling points. If all points have the same orientation without collision — it leaves the group untouched. If not, for every group, it calculates the average orientation, and adjust tool orientations to minimize orientation changes and smooth reversal moves, as shown in Fig. 4.

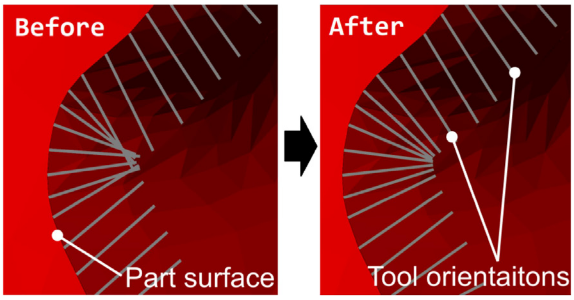


Fig. 4. An example of orientation modifications after smoothing.

There is a rough searching step for every 3rd point and final search for every point involved. The search consists of rough steps of 3°, and then of fine steps of 0.3°. If common orientation found — set values and exit from the function. If not — find subgroups of points with small variation of values within the group. Averages of the found subgroups are considered as stable values. All orientations of the points between stable subgroups and groups are then interpolated.

Finally, all moves are checked for dynamic collision, not only at sample points, but also for all positions continuously by simulation tool motion. In case of collision, the orientation is perturbated only at one sampling point without extra smoothing afterwards is applied. The algorithm does not allow exceeding of the max lead/lag and tilt angles. If the max tilt angle needs to be exceeded in order to avoid the collision, then the toolpath will be split, trimmed and indicated that the collision is not avoided. For a better overview of the algorithm, its simplified flowchart is show in Fig. 5.

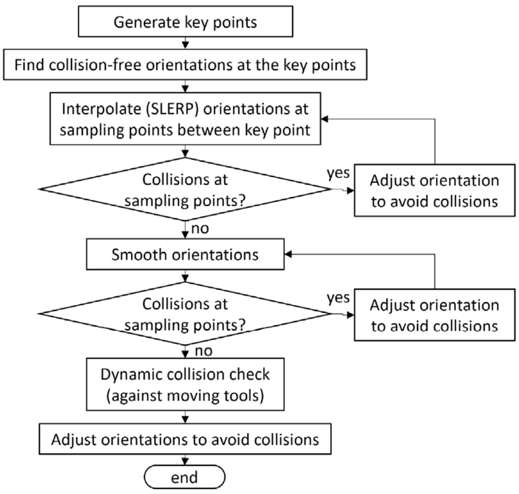


Fig. 5. Workflow of the algorithm.

3. Experimental validation

The experimental validation was tested for 12 double tracks with stepover 1.4 mm. The goal of the experiment is to evaluate the effect of smoothing, sampling distance, and different strategies (one way, zig-zag, tilting, etc.) on the quality of the weld bead. The quality was assessed visually by observing build-up formations and irregularities. The setup configurations are presented in Table 1 and shown in Fig. 6.

Table 1
Parameters of the experiment (per track).

Track	Strategy	Look-ahead distance, mm	Distance between sampling points, mm
1[a]	3 axis	disabled	1–10
2[a]	5 axis	disabled	1–10
3[a]	5 axis	10	1–10
4[a]	5 axis + max angle change 15° (per move)	disabled	1–10
5[a]	5 axis + max angle change 15° (per move)	10	1–10
6	5 axis	disabled	1–10
7	5 axis	10	1–10
8	5 axis	disabled	10–100
9	5 axis	10	10–100
10	5 axis + tilt angle 25°	disabled	1–10
11	5 axis + collision	4	1–10
12	5 axis + collision	4	1–10

[a] Tracks 1–5 are one way, tracks 6–12 are zig-zag.

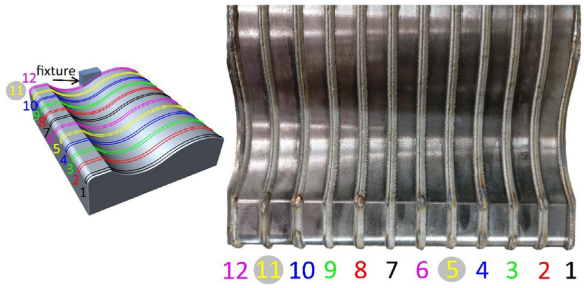


Fig. 6. Geometry and result of the experimental validation (12 tracks).

In order to evaluate the influence of collision avoidance, a virtual fixture has been added to the setup, a prismatic block shown in Fig. 6. This virtual fixture was not present during the actual experiment, as shown in Fig. 7. Observations and short analysis of the different tracks are summarized in Table 2.

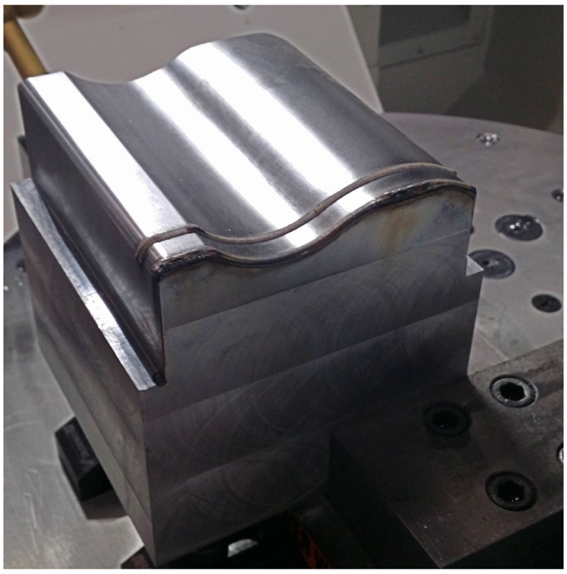


Fig. 7. Actual setup during the experiment.

The experiment was carried out on OKUMA MU 6300 V Laser EX machine with the following settings:

- laser power: 990 W;
- feedrate: 530 mm/min;
- powder type: LPW H13 Tool steel;

Table 2
Observations at the experiment (per track).

Track	Observation
1	This 3-axis toolpath has some defects that can be attributed to the deviation of the tool orientation towards the surface normal.
2	Since the tool follows the surface normal, the build-up peaks in the area of higher curvature are expected. The higher heat transfer into the weld bead is confirmed by the bead color.
3	With smoothing, the quality is better than in track 2
4	By limiting max angle change, the quality at highly curved paths suffers
5	The effect of limited max angle change (track 4) was relaxed by smoothing
6	This is a zig-zag twin of track 2.
7	This is a zig-zag twin of track 3. The difference is not significant. However, there is likely to be a difference between the zig and zag directions.
8	This is a twin of track 2 with fewer sampling points. Reduction of sampling points slightly improved the quality.
9	With a greater point distance, the machine runs a little bit jerky, but the influence of the smoothing is stronger such that the material build-up on the sharp corners are minimal.
10	Since the nozzle was tilted by -25°, the weld bead quality is compromised.
11	Since the smoothing and the collision tilting are used in parallel (due to the virtual fixture), they produce large machine motions of the A and C-axis followed by X, Y, Z. However, the weld bead has decent quality, except the sharp transition. That can be explained by the use of the shorter look-ahead distance of 4 mm, which led to less efficient smoothing.
12	Tilting to avoid collision with the virtual fixture has severely affected the quality of the weld bead.

- powder feed: 6.3 g/min;
- shielding gas type: Argon;
- shielding gas feed: 7 l/min;
- conveying gas type: Helium;
- conveying gas feed: 4 l/min.

4. Conclusions

In contrast to conventional machining, the quality of the DED generated surfaces has appeared to be very sensitive to the feed variation during the process. This feed variation may have different sources. Firstly, the machine dynamics may not reach required levels of angular acceleration and jerk to maintain programmed feed at moves with large angular changes of rotary axes. Secondly, sampling of points of DED toolpaths may influence the CNC of the DED equipment. Too dense sampling points are believed to overfloat the computational capacity of the controller, which will not be able to interpolate all necessary sampling points at the rate of the programmed feed (compare track 2 and track 8 in Fig. 6).

Smoothing of the tool orientation results into better quality of the deposited material at regions where abrupt changes of tool orientation (compare track 2 to track 3 and track 9 in Fig. 6).

Despite smoothing, the weld bead at Track 12 has quality issues due to the tilt angle exceeding an empiric rule-of-thumb limit of 25°. The exact reason of the quality degradation is not known to the authors because the bead formation is a complex phenomenon depending on many factors (reflections, distribution of energy in the laser beam, gas turbulence, etc.).

The presented method is proven to have the ability to improve the quality. The foundation of the presented strategy is based on the combination of automatic tool orientation smoothing and collision avoidance. Important parameters are the lead/lag angles, side tilt angles, sampling distance between toolpath points, look-ahead distance, and full collision avoidance.

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