Abstract

Laser cladding (LC) combined with CAD/CAM can be used to perform rapid tooling and prototyping applications in an industrial environment. Most existing laser cladding processes are adapted into slicing technology, in which a CAD model is represented by a stack of flat and thin layers. Under this strategy, a CAD model is sliced horizontally into a set of planar layers with constant thickness. This paper presents a procedure and an algorithm that allows the slice thickness to be adapted as a function of the arc length of the CAD model geometry. Additionally an adaptive slicing procedure, based on non-planar layers is presented in this paper. For LC on curved substrates it is essential to adapt the slicing plane to the shape of the existing surface. The tool paths are generated by determining the intersection curves between part surface and the curved slicing plane. This can be done by computing the intersection curve between a general parametric surface and a tessellated CAD model. This article also includes a tool path generation procedure using direct slicing. Direct slicing generates precise contour curves for each layer from the solid model and avoids an intermediate representation, such as the STL format. Slicing with curved surfaces and direct slicing is explained on the example of hard-facing of oil drilling tools.

Introduction

Slicing technology is formed to serve the needs of layered manufacturing technologies. Several trajectory planning algorithm have been developed to produce the required paths. In many of them, regardless of the part geometry or processes used to produce the part, the slice thickness remains constant. Under this strategy, a given solid model is sliced horizontally into a set of planar layers, and these planar layers are then built one at a time from bottom up. In this case, planning the build sequence of a given solid model is no more than listening the sliced layers along the building direction, which is straight forward and can be automated easily.

Slicing the layers in a fixed thickness does not usually conform to the part geometry, therefore, the slice thickness may be changed which increasing the production time and sacrifices the part quality. As a result, researchers have developed algorithms that allow the slice thickness to be adapted as a function of both CAD model geometry and the process used to produce the part. This method is called adaptive slicing technology and is state-of-the-art.

The LC process requires new slicing technologies for tool path generation in order to build up complex geometries. In the following several slicing procedures are presented. They are based on continual adjustment of slicing direction and non-planar slicing planes adapted to the existing shape of the base material, respectively. In this connection also the term “adaptive slicing” is used.

Adaptive Slicing for 5-Axis Laser Cladding

In laser cladding, the deposition path generation is dependant on the nature of the deposition process.
As mentioned in [1] 5-axis laser cladding is necessary to build up complex parts with overhangs as opposed to common RP systems which are working in 2.5 D. During 5-axis LC the orientation of the substrate is changed according to the surface normal vector with the advantage of always processing in a downward direction. Thus the influence of the gravity on the melt pool is reduced and flowing down of the melt over the edge can be avoided.

For 5-axis LC simple slicing with constant layer thickness in vertical direction is not sufficient because building direction varies according to the part geometry. Fig. 1 shows the cross section of a vertical thin-walled structure in contrast to a curved structure generated by overlaying single clad tracks. Horizontal slicing with a fixed thickness in z-direction works quite well in the case of a vertical wall but causes gaps in case of an overhanging structure. Horizontal slicing of the part results in a distance $\Delta s$ in building direction, which must be bridged with weld material to provide process stability. To bridge a distance $\Delta s$ with weld material the required number of clad tracks inside a layer is defined as

$$z = \frac{\Delta s}{t_p}$$  \hspace{1cm} (1) 

where $\Delta s$ is the arc length of the contour curve and $t_p$ is the manufacturing layer thickness. The overhang angle $\alpha$ can be written as

$$\cos \alpha = \frac{t_p}{\Delta s}$$  \hspace{1cm} (2) 

where $\Delta s$ is the secant of the arc segment. For small values of layer thickness the overhang angle $\alpha$ can be approximated by

$$\cos \alpha = \frac{t_p}{\Delta s}$$  \hspace{1cm} (3)

Using Eq. 1 and Eq. 3 the required number of clad tracks can be written as

$$z = \frac{1}{\cos \alpha}$$  \hspace{1cm} (4)

Fig. 2 shows the required number of clad tracks for a fixed layer thickness in z-direction as a function of the overhang angle $\alpha$. A particular case is horizontal slicing of a horizontal structure ($\alpha=90^\circ$) which results in an infinity number of clad tracks inside a layer. Thus the slicing direction and thickness must be adapted to the geometry of the part contour, as shown in Fig. 3.

In the following example the part contour is defined by a Bézier curve [2] with the control points $b_0(p_0,q_0)$, $b_1(p_1,q_1)$, and $b_2(p_2,q_2)$. The quadric Bézier curve can be written as

$$C(t) = (1-t)^2 b_0 + 2(1-t)t b_1 + t^2 b_2, \text{ for } t \in [0,1]$$  \hspace{1cm} (5) 

and can be expressed in the parametric form $(x(t),y(t))$ where
Fig. 4 shows a surface of revolution obtained by rotating the Bézier curve with the control points $b_0(2,1)$, $b_1(-1,4)$, and $b_2(6,8)$ about the z-axis. As mentioned above it is necessary to adapt the slicing direction and slicing thickness in order to build such a part using LC.

$x(t) = (1-t)^2 p_0 + 2(1-t)t p_1 + t^2 p_2$, and

$y(t) = (1-t)^2 q_0 + 2(1-t)t q_1 + t^2 q_2$  \hspace{1cm} (6)

For this purpose the surface of revolution is sliced along the Bézier curve which was used to generate the surface. All layers must be equally spaced in building direction with the segment length (layer thickness)

$\Delta s = L_C(b) - L_C(a)$  \hspace{1cm} (7)

as shown in Fig. 5. $L(C)$ is called the arc length of a parametric curve $C(t)$ from $t = a$ to $t = b$. The arc length function is defined as

$L_C(t) = \int_{t_0}^{t} \sqrt{(x'(u))^2 + (y'(u))^2} \, du$ \hspace{1cm} (8)

and measures the length of the curve segment from an initial point $(x(t_0), y(t_0))$ to the point $(x(t), y(t))$ [3]. Assuming the segment length $\Delta s$ (layer thickness) should be 0.8mm for the given Bézier curve, then the parameter $t$ can be computed by solving Eq. 8. Tab. 1 shows the results for $t$ determined by Maple.

<table>
<thead>
<tr>
<th>Layer</th>
<th>$t$</th>
<th>$L_C(t)$</th>
<th>$\Delta s$</th>
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<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
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<td>0.8</td>
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</tr>
<tr>
<td>2</td>
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<td>1.6</td>
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<td>3.2</td>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
<td>8</td>
<td>0.780</td>
<td>6.4</td>
<td>0.8</td>
</tr>
</tbody>
</table>

Table 1. Curve length $L_C(t)$ equally spaced with $\Delta s = 0.8$mm

For this purpose the surface of revolution is sliced along the Bézier curve which was used to generate the surface. All layers must be equally spaced in building direction with the segment length (layer thickness)

Adaptive slicing in combination with the down hand strategy (Fig. 6 to Fig. 7) provides the best results for welding of overhanging parts. Unfortunately adaptive
slicing can only be used for rotation-symmetrically constructed thin-walled (single clad track per layer) parts, since the overhang inside a layer must be constant. Adaptive slicing of 3D parts with any nonlinear geometry is critical because a variation of the surface curvature between the outer and inner contour requires depositing of clad tracks with varying clad height along the tool path within each layer. The so-called non-uniform deposition is practicable but this needs additional expenditure in terms of a controller with the capability of continuously tracking the reference height by varying the laser power and the powder flow.

Fig. 8 shows a surface of revolution consisting of several curve segments. For tool path generation each curve segment was sliced with the mentioned strategy. Afterwards the part was built up by 5-axis laser cladding using the down hand strategy, as shown in Fig. 9.

Adaptive Slicing With Curved Surfaces

LC provides the opportunity for welding on curved substrates, thus layers with a curved surface can be fabricated. To build up nonlinear geometries on curved substrates it is essential to adapt the slicing plane to the shape of the base material. The outline of the curved layer is generated by determining the intersection curve between a tesselated CAD model (part surface) and a general parametric surface (slicing plane). The deposition paths for filling are planned in a parameter-domain as explained below.

Tool Path Generation Using Isoparametric Surfaces

The main task of tool path generation (TPG) is to compute a sequence of laser tool center points (LTC-points) which are calculated so that the clad is tangent to part surface at the clad contact point (CC-point), as shown in Fig. 10. The LTC-point is the corresponding reference point of the laser beam that specifies its location in an NC program [1]. LTC-point computation is carried out in three steps:

1. Mapping: computation of LTC-point for a given “domain-point”.

Figure 7. Down hand position 9.

Figure 8. Wine glass and corresponding surface normals.

Figure 9. 5-axis laser cladding using down hand strategy and adaptive slicing.
2. Marching: find the next domain-point from the current point on the path.

3. Side-stepping: after completion of one path find the initial domain-point on the next path.

The LTC-point computation procedure for isoparametric tool paths will be explained using the slant surface shown in Fig. 11.

In Eq. 11,12 \( S_u(u,v) = (x_u(u,v), y_u(u,v), z_u(u,v)) \) and \( S_v(u,v) = (x_v(u,v), y_v(u,v), z_v(u,v)) \) are the partial derivatives (velocities along latitudinal and longitudinal lines) of the part surface \( S(u,v) = (x(u,v), y(u,v), z(u,v)) \) at the current CC-point. As mentioned the LTC-path computation is carried out in three steps: mapping, marching, and side stepping:

Mapping: The mapping equation for the LTC-point relating to a circular cross section of the clad track is expressed as:

\[
\vec{r}_{lc} = \vec{r}_{cc} + \rho \vec{n} - \eta \vec{k} \tag{10}
\]

where \( \rho \) is the half clad width, \( \eta \) is the distance from the center of the clad to the LTC-point, \( \vec{k} \) is the unit vector called the laser axis vector, which is \((0,0,1)\) for a 3-axis machine, \( \vec{n} \) is the surface normal vector, \( \vec{r}_{lc} \) and \( \vec{r}_{cc} \) are the position vectors to the LTC-point and CC-point, respectively (Fig. 9).

Marching: Assuming that the step-length \( \lambda \) and path-interval \( \delta \) are given, the following updates are made at each marching step [4]:

\[
u = u + \Delta u \quad \text{with} \quad \Delta u = \frac{\lambda}{|S_u|} \tag{11}
\]

\[v = v^* \]

At the begin of the pass \( v^* = v_0 \) (initial value).

Side-Stepping: At the end of each pass, a side stepping is made by updating the domain values as follows:

\[u = u_0 \quad \text{(initial value)}\]
Using the above initial domain-point (CC-point) a sequence of next domain-points is computed by marching along the next tool path.

**Example of Use: Tool Path on Free Form Surface**

The above procedure was implemented into MATLAB. For algorithm verification a tool path of a logo (LLL) was generated on a free form surface. Fig. 12 shows the CC-path on a nonrational Bézier surface which is given by

\[ S(u,v) = \sum_{i=0}^{n} \sum_{j=0}^{m} B_{i,n}(u) B_{j,m}(v) P_{i,j} \quad 0 \leq u,v \leq 1 \]  

(13)

where \( P_{i,j} \) are the control points, \( B_{i,n} \) and \( B_{j,m} \) are the Bernstein basis functions in the \( u \) and \( v \) parametric directions [2].

The CC-paths are planned on the parameter domain of the part-surface, and then they are mapped back to the part surface using Eq. 13. For LTC-path computation each CC-point must be converted to a LTC-point using Eq. 10.

**Slicing Procedure For Non-Planar Deposition Paths**

Generation of non-planar layers requires curved slicing planes, which are represented in parametric form. The contour curve of a curved layer can be calculated by intersecting the CAD model with the curved slicing plane. Generally the part surface is represented in the STL file format, which is a collection of tesselated triangular facets.

Thus the contour curves can be generated by sequentially intersecting each facet with the parametric surface using a SPI (surface plane intersection) algorithm. This is a quite standard practice and will not be discussed in detail. The reader is referred to [5] where this item is discussed at length. Basically the surface can be subdivided into quadrilaterals (Fig. 13), i.e. the surface plane intersection can be performed by calculating the intersection line between the CAD facets and the quadrilateral elements (plane-plane intersection). The slice data include the point data \( P_i = (x_i,y_i,z_i) \) of each contour, the corresponding parameters \((u_i,v_i)\), such that \( S(u_i,v_i) = P_i \) and the normal vector \( \vec{n} \) of the parametric surface. The result of the slicing process is an amount of unsorted line segments in 3D space which are sorted and joined together to form a loop of single contour.

**Figure 12. CC-path on a free form surface.**

**Figure 13. Intersection line between facet and parametric surface**

**Figure 14. Translation of a Bézier curve**
Verification of the Slicing Procedure

The slicing procedure for non-planar deposition paths was implemented into MATLAB.

For software verification several STL models were sliced with an extruded surface which was obtained by translating a Bézier curve (Eq. 5) in the direction of the y-axis. To generate a stack of non-planar slicing planes (Fig. 15) the extruded surface must be shifted by a constant distance $\delta_i$ in z-direction (Fig. 14). This transformation is comparable with the layer thickness or the vertical step $\Delta z$ in the case of planar slicing. Bézier curves are invariant under the usual transformations such as rotations, translations, and scalings, i.e., one applies the transformation to the curve by applying it to the control polygon.

Non-Planar Filling paths

The most important deposition paths are zigzag paths, where the path tracks correspond to back and forth motion in a fixed direction within the boundary. For deposition path generation the contour curve of the layer, generated by intersecting the CAD model with the curved slicing plane, must be mapped to the $u,v$-domain, as shown in Fig. 16.

This task is known as the point inversion problem. Point inversion is the problem of finding the corresponding parameters $u$ and $v$, such that $S(u,v) = P_i$ [2]. Afterwards the tool paths for filling are planned in the parameter domain of the 3D surface, and are then mapped back to the surface $S(u,v)$ as shown in Fig. 17.

Tool Path Generation for Hard-Facing of Oil Drilling Tools

The following example of use demonstrates the application of the non-planar slicing procedure for tool path generation.

The Laser Center Leoben has developed a laser coating process for hardfacing of oil drilling tools. The process armors the drill string component by cladding it with a highly wear resistant layer without impairing the properties of the base material and with minimum distortion. At least as important is the fact that the layer applied by LC bonds reliably to the base material, which is stainless steel alloyed with chrome and manganese. The coating consists of four layers:
1. Buffer layer: ensures the bond to the base material
2. Interface layer: enhances the bond between hardfacing layer and buffer layer
3. Hardfacing layer 1: enhances wear resistance
4. Hardfacing layer 2: enhances wear resistance

Fig. 18 shows the microstructure of the four layers applied to the surface of a drillstring using a Nd:YAG laser.

As mentioned, the cladding regions (contour curves and their inclusion relationships) for non-planar layers can be generated by determining the intersection curve between a parametric surface and a CAD model.

Figure 18. Microstructure of wear-resistant layers on oil drilling equipment

Below the CAD model representing the shape of the desired deposition layer is shown in Fig. 19. The layers are shaped cylindrical with raising and falling edges.

Figure 19. Buffer layer on the tool surface

Figure 20. STL model of the buffer layer sliced with a rational Bézier surface

Figure 21. Non-planar filling paths
For tool path generation the STL model of the buffer layer is sliced by a rational Bézier surface, which is generated by extrusion of a rational Bézier curve representing the planed cladding layers. A rational function is necessary for surface representation because the base material is cylindrical. Fig. 20 shows the buffer layer of the oil drilling tool sliced with a cylindrical Bézier surface. The results of the slicing procedure are the outer and inner contour curves. Fig. 21 shows the non-planar deposition paths for the buffer layer inside the outer and inner contour curves. Non-planar slicing enables the fabrication of arbitrarily shaped layers on existing tool surfaces, as shown in Fig. 22.

Tool Path Generation Using Direct Slicing

Non-planar deposition paths can be generated by non-planar slicing planes, as mentioned before, or by direct slicing using so called “drive-surfaces” [4].

A drive surface is used to drive the laser along the current tool path. The tool path is defined as the intersection curve between drive-surface and part surface. In order to machine an existing surface completely, a number of intermediate tool paths must be defined as a series of drive-surfaces, which are obtained by successively translating the slicing plane along the direction of the unit “drive-surface vector” \( \hat{d} \). Direct slicing generates precise contour curves for each layer from the solid model and avoids an intermediate representation, such as the STL format. Direct slicing of the model keeps the geometric and topological robustness that the original data have.

For deposition path generation on oil drilling tools the solid model of the drilling tool is sliced with a series of planar drive-surfaces along the direction of the drill string axis. The distance between the drive-surfaces is equivalent to the tool path interval \( \delta_v \), as shown in Fig. 23. The tool path is defined as the intersection curve between drive-surface and layer surface.
section function of SolidWorks and MATLAB for deposition path generation. Afterwards a postprocessor converts the machine independent tool paths in a machine specific NC code. Fig. 26 depicts the corresponding edge of the oil drilling tool where the first layer (buffer layer) is applied.

![Image](image1.png)

Figure 25. Tool path pattern for hardfacing of oil drilling tool using direct slicing.

![Image](image2.png)

Figure 26. Buffer layer on surface of oil drilling tool.

### Conclusion

Three different slicing strategies for tool path generation for 3D LC have been presented. The first slicing procedure deals with building overhanging structures with equally spaced layers in building direction which are varied according to the part geometry. This strategy can only be used for rotation-symmetrically constructed thin-walled (single clad track per layer) parts.

The second deals with non-planar slicing planes for deposition path generation on existing tool surfaces. The tool paths are generated using isoparametric surfaces and a tessellated CAD model.

The third slicing procedure deals with direct slicing, where tool paths are generated using a cross-section function of a CAD modeler. The tool paths are obtained by successively translating the slicing plane along the direction of the unit “drive-surface vector” \( \vec{d} \), which is adapted to the tool axis.

Non-planar slicing and direct slicing could be successfully integrated into a laser coating process to accelerate the production and repair process for oil drilling tools. The author summarize all strategies under the term “adaptive slicing”.

### References


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