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HYBRID MANUFACTURING PROCESS FOR RAPID HIGH PERFORMANCE TOOLING COMBINING HIGH SPEED MILLING AND LASER CLADDING

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Abstract

Since the first introduction of rapid prototyping in the 1980's, several techniques have been developed and successfully commercialized. However, most commercial systems currently use resins or waxes as the raw materials. Thus, the limited mechanical strength for functional testing is regarded as an obstacle towards broader application of rapid prototyping techniques. To overcome this problem, direct metal deposition methods are being investigated worldwide for rapid prototyping and even for rapid tooling applications. As a contribution to this development a fundamental study on a process combination of laser cladding technology using YAG laser radiation with high speed milling was carried out and is reported in this paper. The design of the machining centre as well as the hybrid process are introduced. Solutions for upgrading of existing milling centres with a laser and subsystems needed to perform laser cladding, are discussed. As part of the hybrid process the cladded tool is milled every few cladding layers so that very small cutters can be used to reach every part of the tools surface before the next layers are added. Small milling cutters can be used to mill very small corner radii so that the hybrid machining concept will be capable of replacing electro discharge machining (EDM) on many tools. To realize complex parts and overhangs a 5-axis cladding process is needed. This paper presents a procedure and software prototype through which NC tool paths for laser cladding of complex parts on 5-axis machines can be directly generated from a CAD model. It will be possible to manufacture complex structures of fully dense metal and multiple materials. It will be shown that using 5-axis machining for laser cladding allows welding of features that can so far only realized using selective laser sintering in a bed of powder. In combination with the proposed hybrid concept it will be possible to manufacture the most complex and accurate parts. In conclusion, the advantages and disadvantages of this process are discussed. Sample parts e.g. copper alloy parts, nickel-base alloy parts will also be presented.

1. Introduction

In recent years laser cladding technologies has been developed to fabricate dense metal components directly. After the CAD model of the component is sliced electronically into a sequence of layers which define the regions that compose the component, a metal component is fabricated directly through laser cladding layer by layer. This technique has many outstanding advantages, e.g. a metal component can be fabricated much more rapidly and mold free. Many similar methods with the same basic process of fabricating a component have been developed. They are referred to by different names, such as laser engineered net shaping (LENS), laser cladding (LC), laser metal forming (LMF) [1], direct metal deposition (DMD), etc. In this article the process is referred to as LC. During LC, powder is injected into the melt pool through a coaxial nozzle and by scanning the laser beam over the substrate a 3-dimensional, well-bonded coating of various materials can be deposited on the substrate. The layers are added on top of each other, with a vertical step, Δz. Complex parts can be built up layer by layer for rapid prototyping (RP) or repair engineering. The process is shown schematically in Fig. 1. In all RP [2] processes, a computer-aided design (CAD) solid model is sliced into thin layers of uniform, but not necessarily constant thickness in the building direction. The LC process requires a procedure to generate tool path data for the purpose of making 3D layers by a 5-axis controlled NC-machine. The tool path data are created by a software prototype, which is a special CAM software with automatic generation of 3D tool paths. The tool path data include data such as positional coordinates (X,Y, Z) of each layer and rotation angles (A, C) of the turning tables. This also requires additional part information, generated by the slicing software and an algorithm to extract this information on surface contours was developed for this purpose.

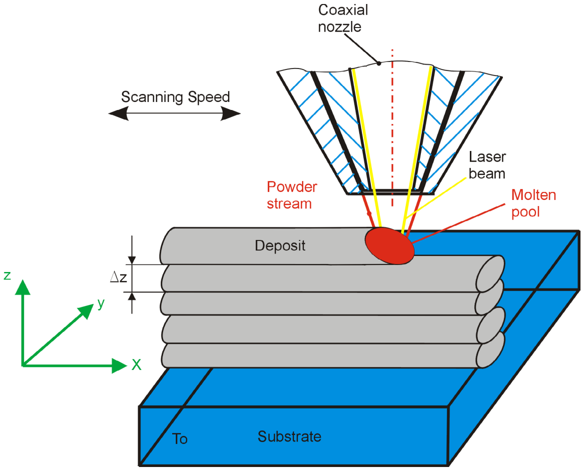


Fig. 1. Schematic representation of the laser cladding process

The LC process is not capable to directly produce parts within the required tolerances and surface quality. Parts have to be finished off on a machine tool. This generally causes additional work for clamping and adjusting of the part to be finished off and also presents an additional source for errors. Finishing off is in some cases done by milling but usually the parts are machined by EDM. This additionally requires the corresponding electrodes to be built. During milling small radii or grooves can only be realized using small milling cutters. These cutters are usually kept short for reasons of stability. Milling of a completed part after build up by laser cladding thus shows the same limitations with regard to accessibility encountered with conventional milling and is possible only to a limited extend. This means, that finishing parts off on a separate machine tool after laser cladding not only costs additional time and effort but also limits the possible geometries. To overcome these limitations a milling machine for high speed machining (HSM) was fitted with a laser to form a hybrid machining centre capable of alternate laser cladding and milling. Because of the low depositions rates during laser cladding in comparison to removal rates during milling laser processes can only establish themselves in areas where milling down a massive block is economically not feasible or where the layer wise deposition offers alternative advantages. Some examples includes build up of parts from expensive or difficult to machine materials like titanium or stellites, the refurbishment and hardfacing of used or premachined tools as well as building dies and moulds with integrated conformal cooling structures made of highly heat conductive alloys very close to the surface.

2. The Hybrid Concept

Because parts build by laser cladding shows a certain amount of distortion and dimensional tolerances a subsequent machining step is required. To overcome the need for additional machine tools the idea for a combined machining centre arose [3,4]. This hybrid machine concept allows three dimensional parts to be generated with high accuracy. By alternately welding and milling parts with deep cavities can be build that would normally require EDM to realize. Due to the layer wise machining where only the last, uppermost layers are machined very short and small milling cutters may be used. However, small milling cutters require high rotational speeds to reduce the cutting forces. Due to the precise laser cladding process only very little material needs to be machined away. There is no need for roughing operations with the laser cladded part being evenly oversized. Because cladding layers are relatively thin (< 1mm) only small depth of cuts are required during milling.

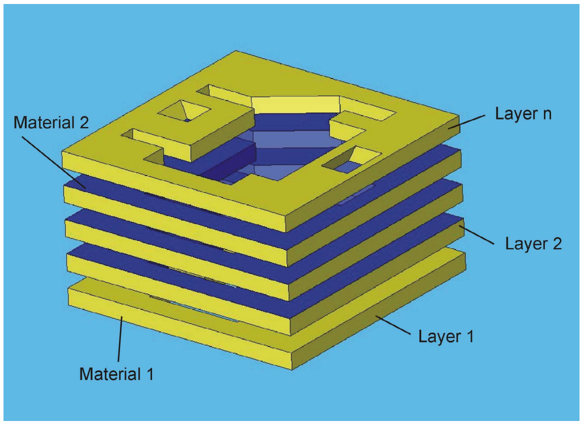


Fig. 2. Combination of different metals within one part.

The use of a metal powder for laser cladding rather then wire allows the combination of different metals within one part (Fig. 2). Because of the alternate machining no cooling liquids may be used during milling. In laser cladding very tough alloys are used for the top layers for one to enhance tool performance for the other because after milling full heat treatment is not possible and because material costs are secondary with this specialized rapid tooling process. For milling of these high strength alloys a specialized milling process is needed. As a milling process that is capable of fulfilling all of the above mentioned criteria a high speed milling (HSM) process and machinery was chosen.

3. Design And Construction Of The Milling Centre

To realize the hybrid process consisting of laser cladding (LC) and high speed machining (HSM) a conventional five-axis milling machine (Röders RFM 600 DS) was fitted with a Nd:YAG laser cladding nozzle (Fig. 3) and a powder feeding unit. The combination within a five-axis milling machine is sensible because both processes require a five-axis CNC controlled positioning device. The mechanical properties in terms of speed and stiffness are determined by the milling process since the laser is a non-contact tool. Because of the slow welding speeds and low additional weight of the laser cladding nozzle no additional dynamic demands exist.

For attaching the laser cladding nozzle to the existing machine two possibilities exists:

1. The laser nozzle and focusing unit is equipped with a taper for attachment to the spindle like a normal tool. While this variant retains the entire workspace in the XY plane, working space in the z direction is considerably reduced. Also it is not possible to put the laser nozzle into the tool magazine because of the required beam guides, cooling water and gas hoses.

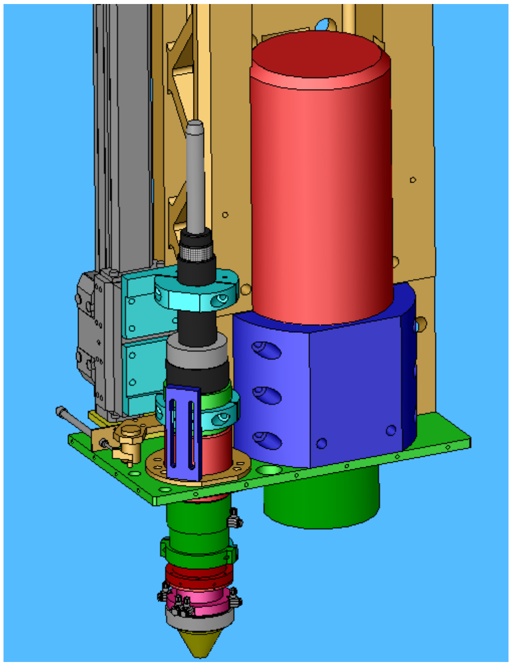


Fig. 3. Laser cladding nozzle and focusing unit.

2. The laser nozzle and focusing unit is attached to one side of the spindle. Here the working space in the z direction can remain unchanged, but the XY plane is reduced. Reduction here depends mainly on the size of the frame to which the spindle is attached (Fig 4). Again HSC (High Speed Cutting) machine tools offer some advantages because they are build slimmer.

Fig. 4. Reduction of the working space in XY plane.

Variant 2 offered the best solution for adapting a small sized HSC machine while retaining practically the whole working space. The laser cladding nozzle was mounted on a pneumatically driven linear guide directly adjacent to the spindle in the z direction (Fig. 5). To retain as much of the working space in the XY plane special care was taken during the design of the support for the laser nozzle and focusing unit to position the laser beam as close to the spindle axis as possible. Also the laser nozzle was especially optimized for a small diameter to further reduce distance.

To protect the laser components during milling operations the whole assembly can be retracted into the spindle casing.

For the beam guide as well as the powder and cooling water hoses an additional flexible cable carrier system was integrated into the machining centre.

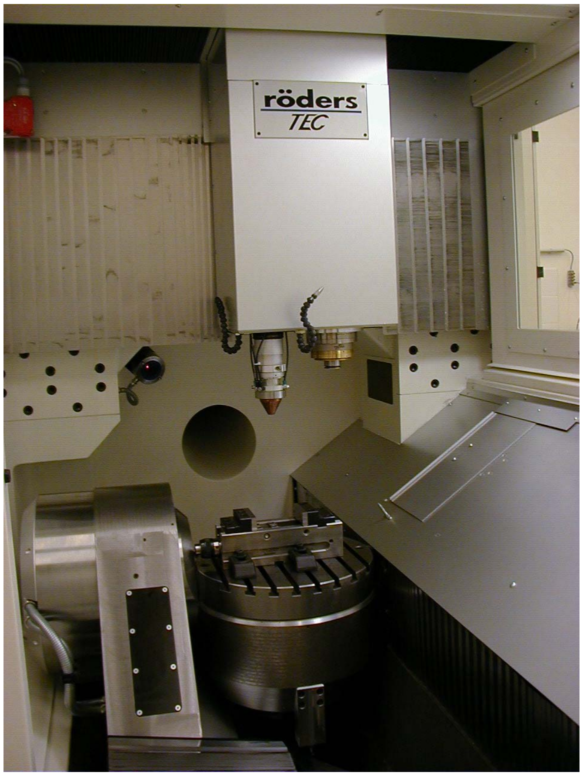


Fig. 5. HSC milling machine combined with a Nd:YAG laser cladding nozzle.

3.1 Powder Feeding System

To allow laser cladding and high speed milling in one machining centre a powder feeding system had to be included (Fig. 6).

Fig. 6. Powder feeding system.

By using powder instead of wire as a weld additive the process is more robust against misalignment and more easily automated. By using more then one feeding unit it is possible to change the cladding material during cladding or even mix different powders while working. Ideally the powder is injected coaxially to the laser beam via a coaxial nozzle. The powder feeder consists of two feeding units with the possibility to separately adjust the powder feeding rates for each system. The powder itself is transported by a carrier gas (e.g. argon) through antistatic tubes via the nozzle to the working zone. The system itself is accommodated in a divided control cabinet with the actual feeding system being separated from the electrical system. The whole feeding unit is totally integrated into the CNC control system of the machining centre.

3.2 Extended CNC-Control

Standard CNC controllers as they are used for HSC machines can also be used to control the laser cladding process. To control all the additional systems automatically through the CNC a few extra outputs had to be included and the finite state machine had to be adapted to include the new machine conditions. One difference to the milling process however lies in the fact that the laser cladding process is much more dependant on precise and constant feed rates and that a very quick control of the laser power is crucial. The laser power (Fig.7) can be controlled as a function of input parameters i.e. the actual feed rate F. Control function is limited to a third order polynomial (P_0, P_1, P_2, P_3) and can additionally be held between a lower (P_{min}) and upper limit (P_{max}).

$$P(F) = P_0 + P_1 \cdot F + P_2 \cdot F^2 + P_3 \cdot F^3 \tag{1}$$

$$P_{\min} \leq P(F) \leq P_{\max} \tag{2}$$

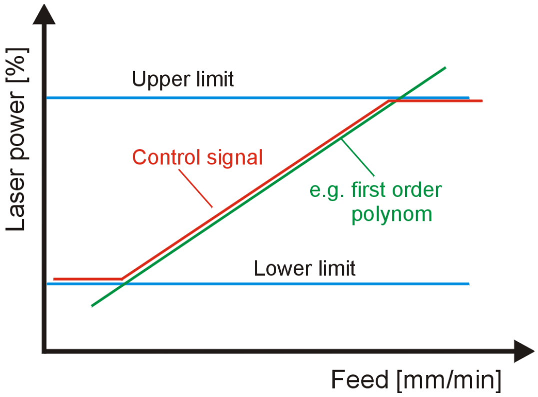


Fig. 7. Laser power control.

4 5-Axis Laser Cladding

Using 5-axis machines provides the possibility to produce the most complex parts with laser cladding. Initial trials proved that it was possible to produce overhanging walls up to 30° with only three axes (x, y, z) systems. Building this way results in the thinning of the wall with the eventual loss of component shape and the LC process collapse.

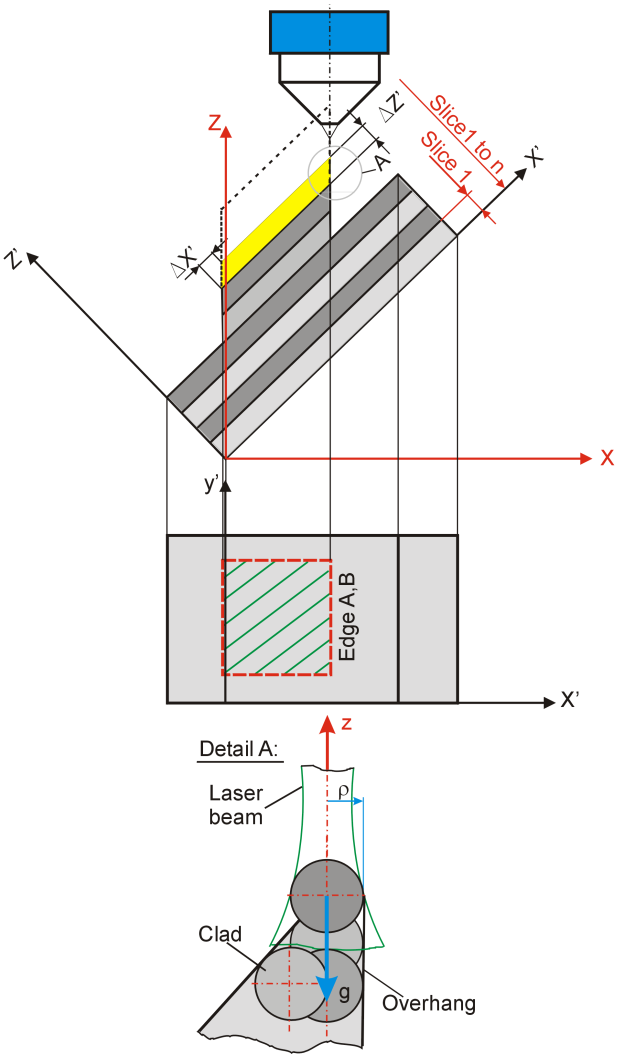


Fig. 8. Down hand strategy.

Additionaly the melt pool is effected by the gravity and so the melt flows down the side. These build problems can be avoided by 5-axis machining. By changing the orientation of the substrate, with respect to the fixed processing nozzle, a 3D path can be presented with the advantage of always processing in a down hand direction. With the ‘down hand strategy’ it is possible to realize arbitrary overhangs (Fig. 8). Unfortunately local collisions between the nozzle and the part being machined have to be considered. The main problem of 5-axis machining is linked to the necessary change of coordinate system that transform the coordinates of tool path, initially in the workpiece coordinate system (P-system) into motion orders of the axes. The CAD/CAM system calculates a tool path defined by a set of successive tool positions expressed in the P-system. The tool path so calculated is thus machine independent. A laser beam position is given by the position vector of the laser spot, $\vec{x}(x_p, y_p, z_p)$, and by the unit vector associated to the laser axis direction, $\vec{q}(i, j, k)$. Both vectors are expressed in the P-system (Fig. 9). Note that the tool trajectory always expresses the movement of the laser relatively to the part contour. The laser tool center (LTC) point follows the tool path, which is calculated so that the contact point between the clad and the part surface contour (clad contact point) approximate the surface within a given tolerance. A clad contact (CC) path is a series of CC-points where the clad is tangent to the part surface being deposited, while a LTC-path is defined as a sequence of LTC-points. The description or interpolation format of the tool path is mostly linear. The tool path consists of a set of successive tool positions linked one to the following by a line segment. Basically, the configuration of a serial structure 5-axis machine is characterized by three translation movements (x_m, y_m, z_m) and two rotations (A and C for example). Therefore, it is necessary to transform the variables x_p, y_p, z_p, i, j and k associated to one tool position into five position instructions x_m, y_m, z_m, A and C, that means 5 orders of axis movement. This transformation is denoted the inverse kinematics transformation, and strongly depends on the structure of the studied machine. Standard NC units carries out the inverse kinematics transformation in real-time, but only for one tool center point (TCP). To allow alternation between 5-axis laser cladding and milling two 5-axis transformations are required, one for each tool center point. The machine control is capable of automatically switching between the two transformations (RTCP-functions).

The generation of 3D layers by a 5-axis NC machine requires a procedure to generate tool path data (LTC-points) that is completely different from that of conventional RP CAM systems. The cladding regions (contour curves and their inclusion relationships) for individual slices or layers can only be generated via a

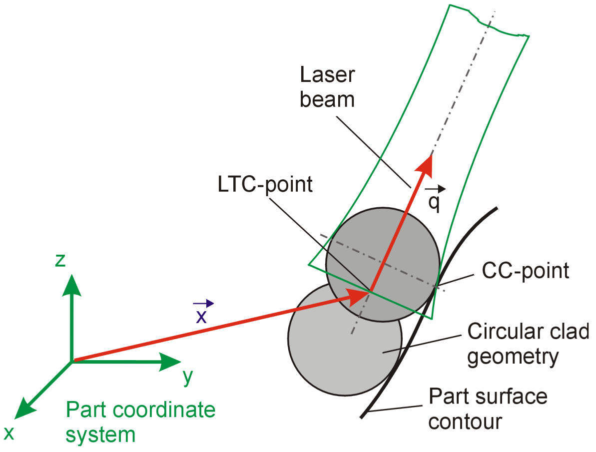


Fig. 9. Laser beam positioning in the part system

query of the solid model. The part surface is normally represented in the STL format, which is a collection of tesselated triangular facets. For a conventional RP system the STL file would be sliced into 2D data only. For 5-axis LC additional part informations, e.g. the normal vector $\vec{N}(Nx, Ny, Nz)$ of the triangular facet belonging to each CC-point is necessary. The following algorithm has been implemented in a CAM software prototype for use with the LC process:

Step 1: Convert a 3D CAD model into a triangular facet file format, the STL file (Fig. 10).

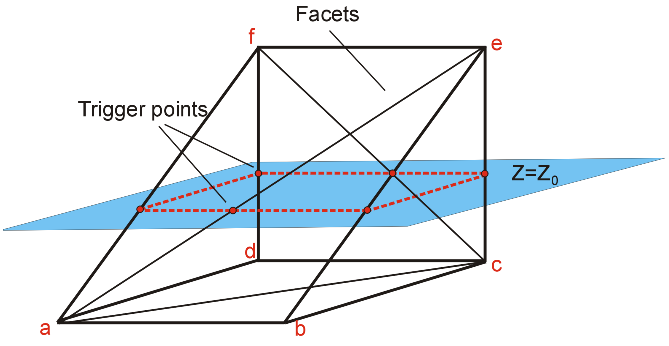


Fig. 10. Slicing STL Data

Step 2: Read the STL file of the model and store the data for all facets in a convenient and systematic way.

Step 3: Set the height value $z=z_0$ and look for all triangular patches which cross the plane at a specific z-height. Calculate the crossing segments with each triangle and sort and connect the segments to form a loop of single contour. The slice data include the point data (X,Y,Z) of each contour and the normal vector $\vec{N}(Nx, Ny, Nz)$ of the triangular facet. The intersection points (trigger points) correspond to the CC-points (Fig. 11).

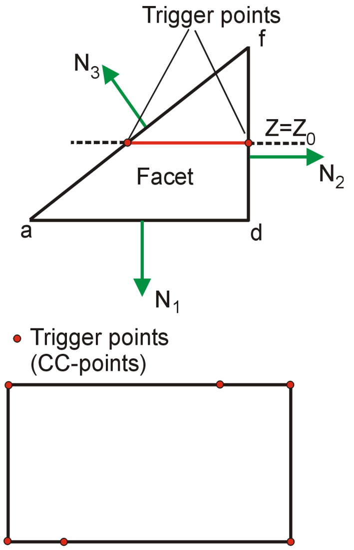


Fig. 11. Slicing triangular patch

Step 4: Sequencing all these CC-points in a given loop to create a CC-path and calculate the LTC-path with a 2D-offset algorithm [5] (Fig. 12).

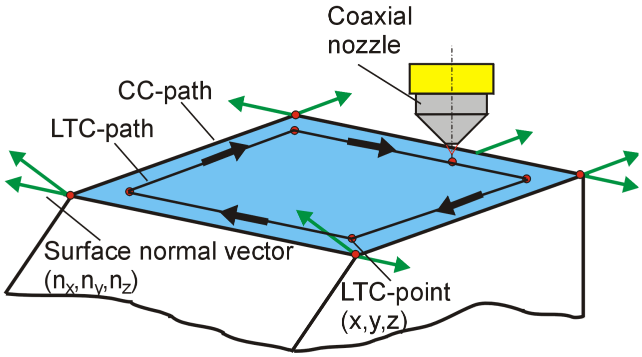


Fig. 12. Generated tool path for LC

Step 5: Repeat this procedure until $z=z_n$ (Fig. 13**)**.

Step 6: Use geometric relations to generate 5-axis CNC-Code for tool movement from one tool position to another

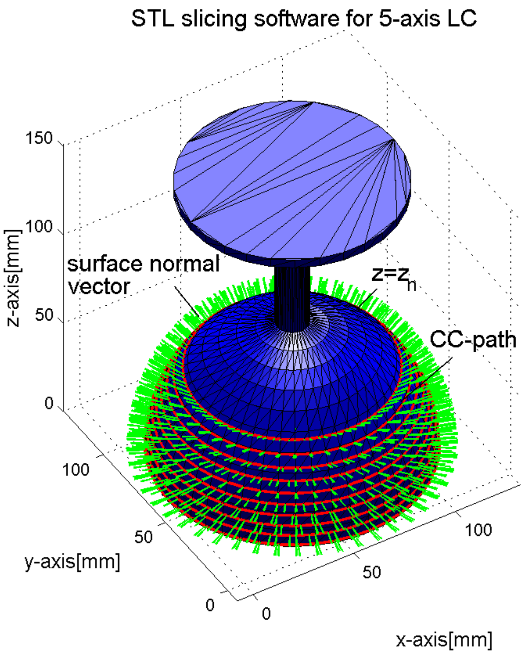
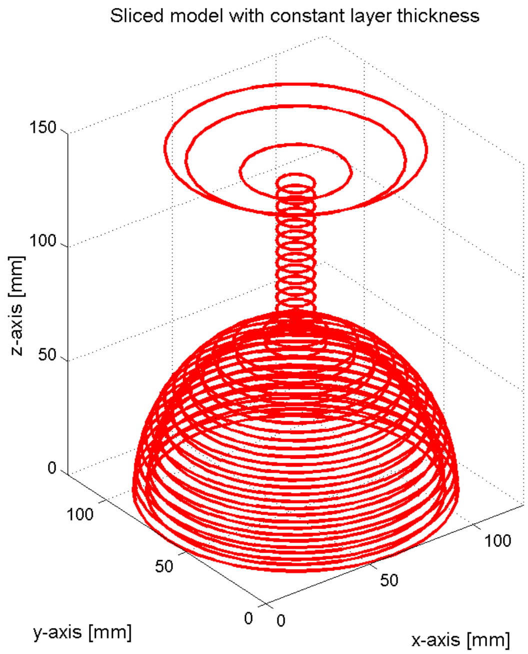


Fig. 13. STL slicing software for 5-axis LC



5 Tool Path Generation For Laser Cladding And Milling

To make programming of the hybrid machine economical tool paths [6] for laser cladding as well as milling have to be automatically generated by software for computer aided manufacturing (CAM). Tool path generation for laser cladding fundamentally differs from strategies used for milling. The main difference lies in the fact that with laser cladding material is added with every layer as opposed to material being removed in the case of milling and distance between adjacent tool paths needs to be constant during laser cladding. Also exit and entry macros are entirely different as with laser cladding. The timing of the laser shutter and feed rates are used to control start and finish of a cladding track. For milling operations tool paths are generated in relation to a block from which the finished part will be milled. Some milling strategies have been found suitable for the hybrid concept. 2D contour milling (Fig. 14) and plain milling (Fig. 15) could be integrated successfully into the hybrid process. Because the seize of the cladding tracks varies a certain allowance has to be considered. Milling is usually done in only two steps. The first one being a roughing step to give a well defined dimensional tolerance and a second finishing step that takes away about 0,1 mm to give final dimensions [7]. During every milling step a well defined geometry is produced that forms the basis for the next cladding operations (Fig. 16).

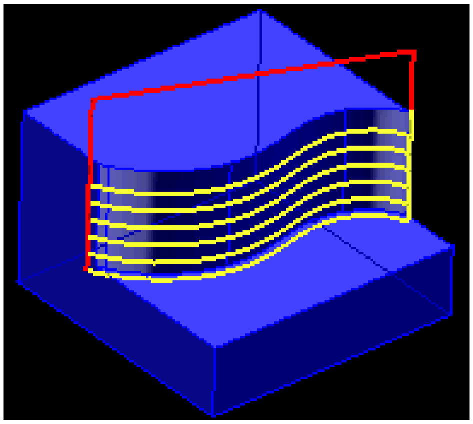


Fig. 14. 2D contour milling

This way instabilities in the cladding process are easily compensated without the need for complex weld pool sensors. Because in the plane of welding the laser cladding tracks are accurate to below 1 mm. The amount of material that needs to be removed is small an tool collisions during milling can be avoided.

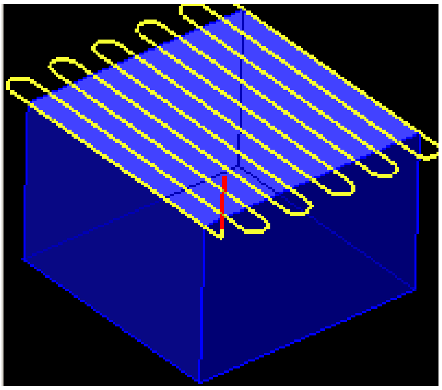


Fig. 15. Plain milling

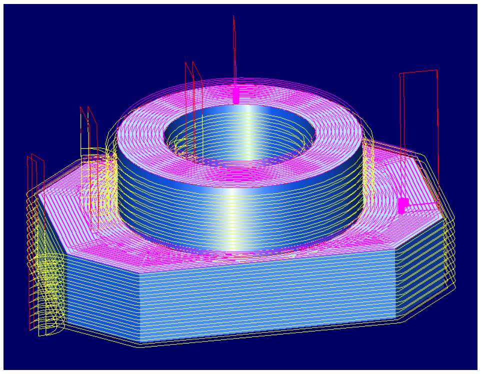


Fig. 16. Tool path generation for milling

Generation of cladding tracks takes place in two steps:

1. Generating tool paths for contour welding: During contour welding only the outer and inner contours in the corresponding plane are welded. Using the simultaneous 5-axis positioning (down hand strategy) overhanging structures can be generated without the need of any support structure.

2. Generating tool paths for filling: After the contour of a layer has been built up, the space in between is filled with weld tracks each separated by a well defined distance from the next [8]. When crossing island within the layer that don't need filling, the laser is simply turned off very similar to moving a milling cutter to safety height. Because the contour offers the necessary support in many cases filling can be performed as a 2 ½ dimensional machining process (Fig. 17).

Fig. 18 shows a part that was built with the referred process. Laser cladding was carried out at 0.8 mm growth per layer. Two alloys, a nickel based alloy and copper, were used during the process.

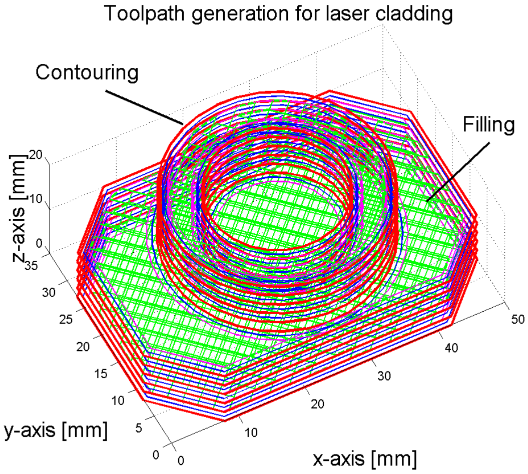


Fig. 17. Tool path generation for LC

The whole part was built in 4 hours starting with a finished CAD drawing.

Fig. 18. Part fabricated by the hybrid process

6 Results And Conclusions

It was possible to include the LC process into an existing machine tool with only minor changes by combining laser cladding and high speed milling. High spindle speeds (42.000 RPM) enable dry machining and milling with small milling cutters to produce small radii. Major advantages [9] of high-speed machining are reported as: dry machining, high material removal rates, the reduction in lead times, low cutting forces, dissipation of heat with chip removal resulting in decrease in workpiece distortion and increase part precision and surface finish. The common disadvantages of HSM are claimed to be: excessive tool wear, need for special and expensive machine tools with advanced spindles and controllers, fixturing, balancing the tool holder, and lastly but most importantly the need for advanced cutting tool materials and coatings. Due to an alternation between laser cladding and milling deep cavities can be produced that normally require EDM. Fig. 18 shows a nickel-base alloy part in combination with copper fabricated by the hybrid process.

Initial trials proved that it was possible to produce overhanging walls of up to 30° with only 3-axis machining. So we have developed a procedure and a software prototype through which NC tool paths for laser cladding of complex parts on 5-axis machines can be directly generated from a STL-CAD model. For tool path generation we employ a boundary extraction algorithm to compute the contour curves and the normal vector $\vec{N}(Nx, Ny, Nz)$ of the triangular facet belonging to each point. The normal vector is used for substrate orientation. It was possible to produce the most complex parts with laser cladding by using 5-axis machines (Fig. 19).

Fig. 19. Wineglass fabricated by 5-axis LC

In combination with high speed milling parts can be build from scratch that would otherwise require numerous machining steps including milling, heat treatment and EDM. The hybrid machining concept reduces problems with positioning and clamping of premachined parts as well as the logistical effort. Ultimately this allows parts to be built from scratch combining different materials within one body. Parts of high strength and surface hardness without heat treatment can be fabricated. Finished parts machined to tight tolerances and high surface qualities without any need of finishing off as encountered with so many other rapid tooling methods can be produced.

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