Solid Freeform Fabrication 2017: Proceedings of the 28th Annual International
Solid Freeform Fabrication Symposium – An Additive Manufacturing Conference
Reviewed Paper

5-AXIS SLICING METHODS FOR ADDITIVE MANUFACTURING PROCESS

Sajan Kapil*, Seema Negi*, Prathamesh Joshi*, Jitendra Sonwane*, Arun Sharma*, Ranjeet Bhagchandani* and K. P. Karunakaran*

*Mechanical Engineering Department, Indian Institute of Technology Bombay, Powai, Mumbai, 400076, Maharashtra, India

Abstract

In metallic *Additive Manufacturing (AM)* processes such as *Hybrid Layered Manufacturing (HLM)*, it is difficult to remove the support material used for realizing the overhanging/undercut features. Multi-axis kinematics can be used to eliminate the requirement of the support mechanism. In this work, two slicing methods have been proposed which utilize the benefits of multi-axis kinematics to eliminate the support mechanism. In the first method, planar slicing is used and the overhanging/undercut features are realized while keeping the growth of the component in the conventional Z-direction. In the second method, non-planar slicing is used, and the growth of the component need not necessarily be in the Z-direction; it can also be conformal to the selected feature of the component. Both these methods are explained through a case study of manufacturing an impeller by the HLM process.

Keywords: Hybrid Layered Manufacturing, Rapid Prototyping, 5-Axis Cladding, 5-Axis Slicing, Non-planar Slicing

Introduction

Hybrid Layered Manufacturing (HLM) uses cladding units such as *Metal Inert Gas (MIG)*, *Tungsten Inert Gas (TIG)* and *LASER* for material addition and conventional machining operation for material subtraction. This synergic combination of material addition and subtraction process makes HLM an optimal method for metal based *Additive Manufacturing (AM)* processes. In our indigenous HLM process, the cladding units are retrofitted with the existing 3/5-axis CNC machines without disturbing their other capabilities, see Figure 1.

(a) 3-Axis HLM | **(b)** 5-Axis HLM

Figure 1: Experimental setup of Hybrid Layered Manufacturing process

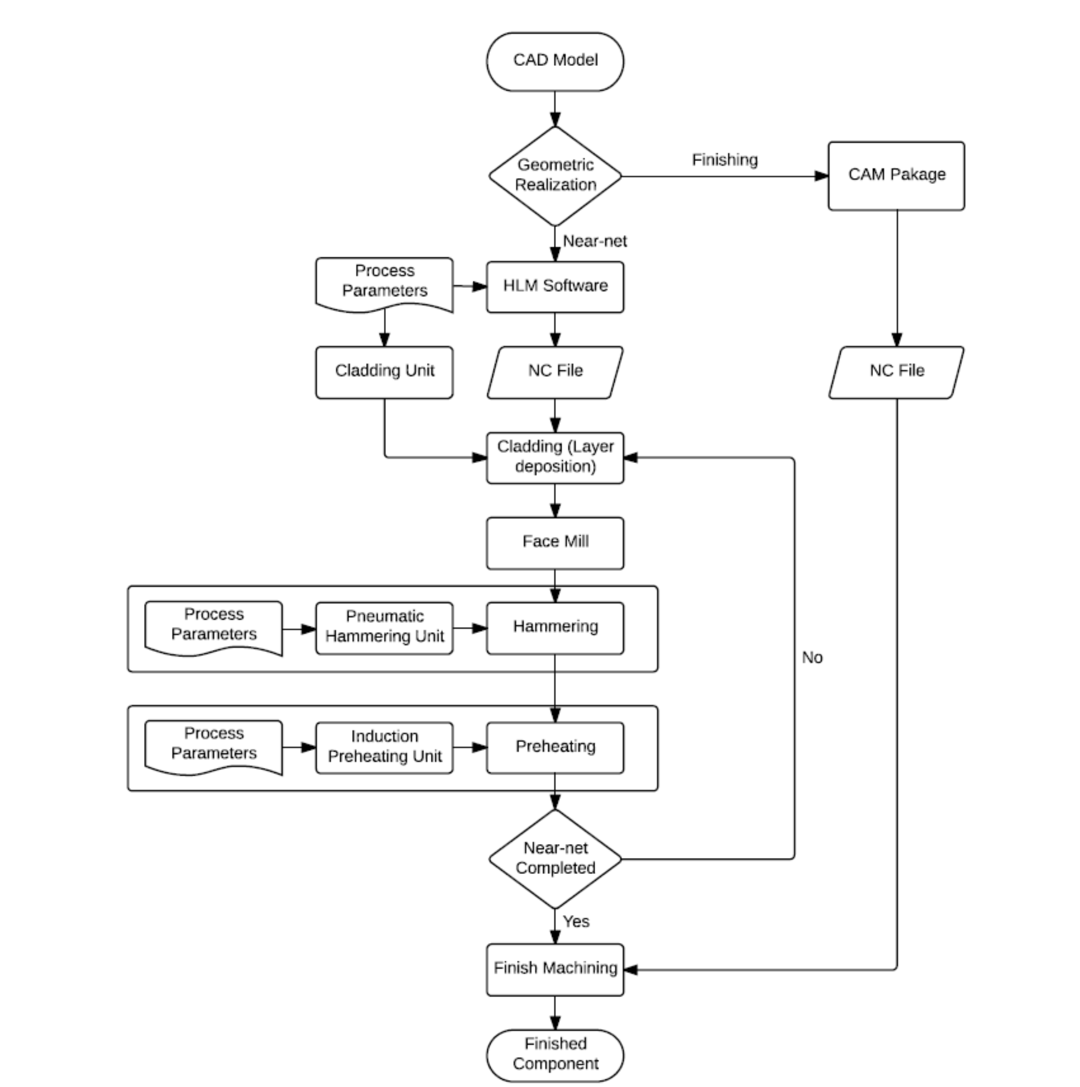


Figure 2: Flow chart of Hybrid Layered Manufacturing process

A typical flow chart of the HLM process is shown in Figure 2. For the geometric realization of a component, a valid CAD model is used as input to the HLM software which generates NC files corresponding to each layer as output. The generated NC files are then used to move the cladding units in the required region on the substrate for the realization of each layer. After deposition of each layer, three in-situ processes are used viz; (1) Face-milling (2) Pneumatic hammering and (3) Induction preheating. The Face-milling operation is used to maintain the Z-accuracy, remove the scallop and oxide scale. The pneumatic hammering is used for relieving the stresses developed during the solidification of deposited material. An induction-based preheating system is then used to heat up the prebuilt layer before deposition of next layer. By repeating these steps for each layer a near-net shape of the geometry can be realized. This near-net shape is then finished by milling to obtain the final finished product. The cladding units can be retrofitted with the 5-axis CNC machine to eliminate the need for support material, Figure 1b. By utilizing the multi-axis kinematics the relative position between cladding unit and a prebuilt layer is set in such a way that the overhanging/undercut features can be deposited without using any support mechanism. Several strategies have been proposed for multi-axis AM by many research groups. A literature survey has been carried out which is summarized in the following paragraph.

The AM processes which use multidirectional deposition can reduce the amount of sacrificial material deposited. A methodology has been proposed by Singh and Dutta [1] for 5-axis slicing algorithms of a component. The main objective of the work was to select the build direction of different subvolume such that the support material can be eliminated/reduced and a collision -free deposition tool path can be generated. A similar approach has been adopted by Sundaram and Choi [3] for 5-Axis laser aided *Direct Metal Deposition (DMD)* process. They build the component in the +Z direction and the orientation of the object changes for deposition of the different subvolumes. In the work of Zhang [2], an algorithm has been developed for adaptive slicing for a 5-axis hybrid *Laser Aided Manufacturing (LAM)* process. The overhang features in a hybrid LAM process are produced without support material by using two strategies: (a) Deposition of overhang on transition wall, (b) Deposition of overhang based on surface tension. 5-axis Hybrid Layer Manufacturing systems, where the deposition is done along with a subtraction process are capable of producing non-uniform layers thickness [4-6]. Hence with the integration of multi-axis deposition and machining processes on the same workstation, a hybrid system is able to produce complicated geometry. In the work of Ren et al. [7], the process planning strategies for 5-axis deposition is proposed by following steps (a) spatial decomposition (b) slicing of the part (c) tool path generation. In the work of Singh and Dutta [8], a method has been proposed for slicing in non-planar/multi-direction called "Offset Slicing". As the multi-direction deposition allows the deposition of 3D slices, these three-dimensional slices should be parallel to each other and the base (i.e. offset) to maintain a uniform thickness. Ruan et al. [9] have proposed a method for deposition of non-parallel and non-uniform layers to reduce the staircase effect. To deposit such 3D layers, this method uses an empirical model to predict the layer thickness. In the work of Ren et al. [10], an integrated process planning for Hybrid manufacturing system is presented. A hybrid process planning software has been developed which has the capability of automatic alignment of layers to avoid a support structure, automatic collision detection with a pre-deposited layer, adaptive tool path generation to avoid the voids in a contour parallel toolpath and automatic 5-axis finishing machining after deposition. As discussed earlier in [4] to produce non-uniform slicing, if the machining is done on an STL file the accuracy may not be good hence Zhang et al. [11], proposed a method for improving the accuracy of 5-axis machining of each layer. A Continuous 5-axis laser cladding process has been recently studied by Calleja et al. [12]. They have performed the experiments to study different toolpath strategies and to arrive at an optimal toolpath considering quantitative criteria such as the deposition rate, the wetting angle and the height and width clad tracks.

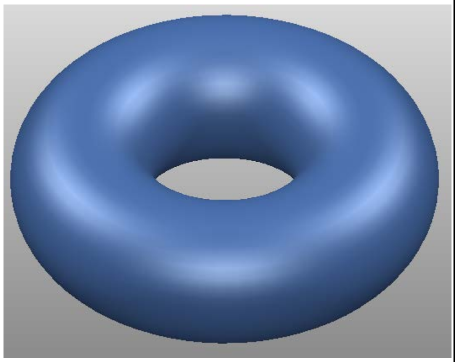
From the above literature review, it can be summarized that in all the 5-axis based deposition methods a 5-axis machining operation is required to develop non-uniform layer. In this work, two unique slicing methods have been proposed for depositing the layers continuously through 5-axis. HLM process has been used for the experiments and the validation of the developed slicing procedure.

Methodology and Illustration

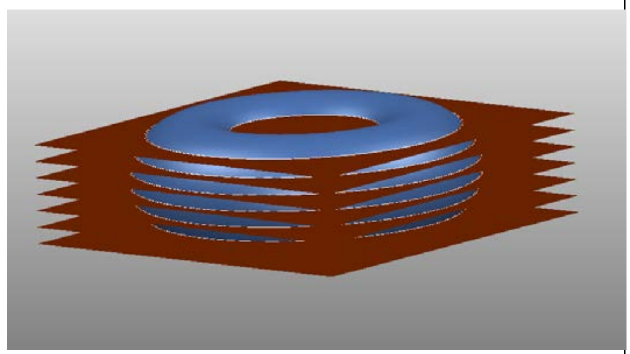
In this work, the slicing procedures have been classified on the basis of the kinematics involved in the deposition of a layer viz; (a) 3-axis slicing and (b) 5-axis slicing procedure. Both the slicing methods are explained in the following sections

3-Axis Slicing

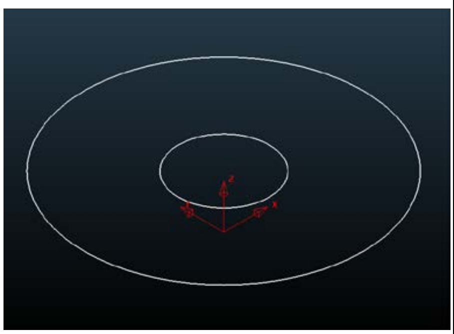
If only 3-axis kinematics is involved for the realization of a layer then it will be called 3-axis slicing method. To realize a layer, the slice is consist of two tool paths viz; (a) outer contour deposition and (b) inner area-filling. For each layer first, the outer contours are deposited then the inside area is filled. Figure 3 shows the steps involve in 3-axis slicing method. For inside area-filling, several methods are available such as direction parallel, contour parallel and other area-filling strategies [13].



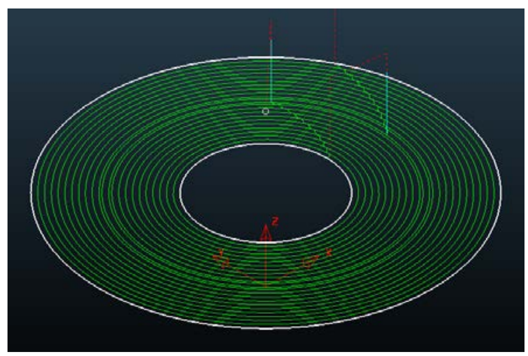
(a) CAD model of the component



(b) 3-axis slicing of a component



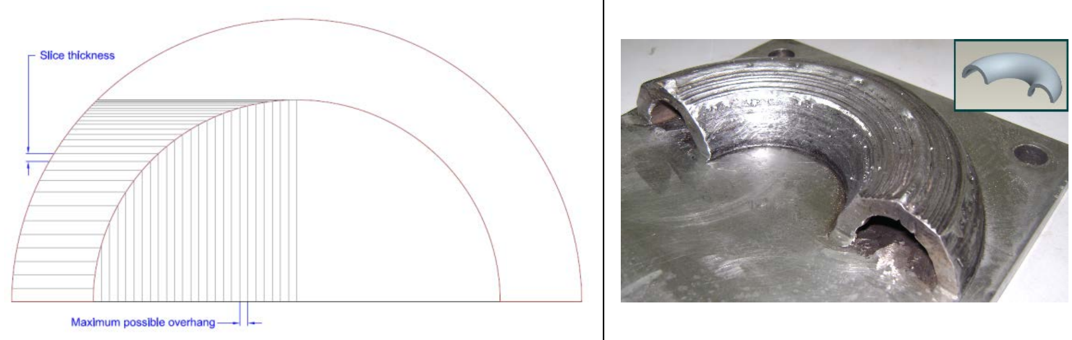
(c) Intersecting outer contours in a slice



(d) Inside area filling by contour parallel toolpath

Figure 3: 3-axis slicing procedure

While depositing the outer contours it should be noted that if the overhanging feature is beyond a limit (which depends upon the surface tension of the material), then it will be required an external support mechanism. For example, a slant wall of Mild-steel with an angle of 30° from vertical can be easily manufactured by 3-axis slicing without using any support material. Adaptive Slicing is one method of manufacturing the overhanging features on 3-axis. In this method, the CAD model is sliced with varying layer thicknesses. The region of the object with a higher gradient with respect to the build direction is sliced with a smaller layer thickness and vice versa. If the current layer overhangs the previous one beyond a limit then adaptive layer thickness method can be utilized as shown in Figure 4.



(a) Variable layer thickness in circular duct | **(b)** Actual deposition of the duct

Figure 4: Adaptive slicing method

5-Axis Slicing

As discussed above, if the overhanging feature is beyond a limiting value then an external support mechanism will be required. To eliminate the need for the external support mechanism a 5-axis kinematics can also be utilized. In this section, two methods have been proposed for continuous 5-axis deposition viz; (a) planar slicing and (b) non-planar conformal slicing. Both the methods are described below:

Planar Slicing

In the case of planar slicing method, the component is still built in the similar way as discussed in the previous section for 3-axis slicing. The only difference will be in the deposition of the outer contours. While depositing the outer contours the cladding torch vector need to be aligned with the tangent vector as shown in Figure 5a. Once the outer contours are deposited by tilting the cladding torch or substrate along the tangent vector a bowl kind of shape is prepared, see Figure 5b. Now the inside area can be filled as earlier using the 3-axis kinematics, as shown in Figure 5c. Each layer is deposited by repeating the same steps.

As discussed above the torch vectors need to be calculated for outer contour deposition in each slice. To calculate the torch vectors, cross product method can be used. If in the i^{th} slice, the torch vector is t_i then it can be defined as:

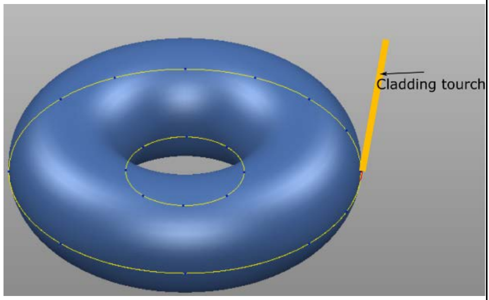
$$\hat{t}_i = \frac{\hat{n}_i \times (\bar{\mathrm{p}}_{\mathrm{i+1}} - \bar{\mathrm{p}}_i)}{\|\hat{n}_i \times (\bar{\mathrm{p}}_{\mathrm{i+1}} - \bar{\mathrm{p}}_i)\|}, \qquad (1)$$

where $\hat{n}_i$ is the unit normal vector in the motion path containing $\bar{p}_i$ and $\bar{p}_{i+1}$ points. It can be noted that the tilting of the torch is required only for overhanging features hence it is necessary to identify the overhanging feature in the component. If the building direction is $+\hat{k}$ then for an overhanging feature the following condition has to be satisfied.

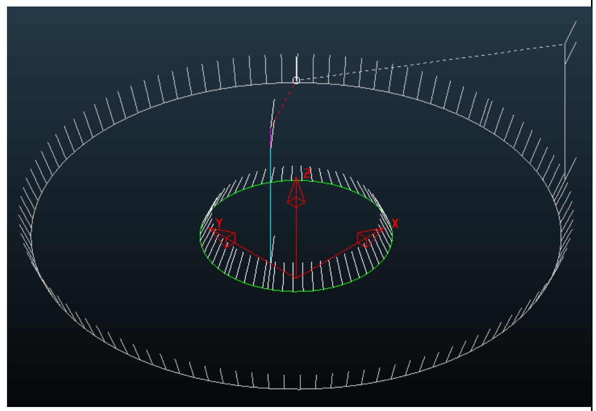
$$\hat{n}_i . \hat{k} < 0 \qquad (2)$$

Hence now one can write the torch vector in the following form.

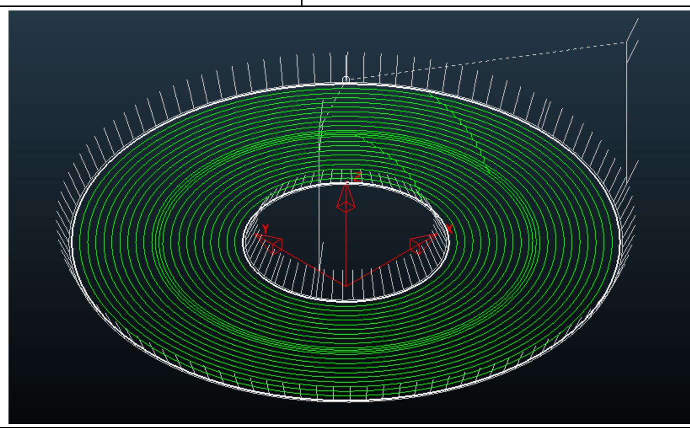
$$\hat{t}_i = \begin{cases} \dfrac{\hat{n}_i \times (\bar{\mathrm{p}}_{\mathrm{i+1}} - \bar{\mathrm{p}}_i)}{\|\hat{n}_i \times (\bar{\mathrm{p}}_{\mathrm{i+1}} - \bar{\mathrm{p}}_i)\|} & \text{if} \quad \hat{n}_i . \hat{k} < 0 \\ \hat{k} & \text{if} \quad \hat{n}_i . \hat{k} \geq 0 \end{cases} \qquad (3)$$



(a) Cladding torch along the tangent vector



(b) 5-Axis toolpath for outer contours in an intermediate slice with torch vector



(c) 3-Axis inside area filling of the intermediate slice

Figure 5: 5-Axis planar slicing method

Non-planar Conformal Slicing

In this method the slices are conformal to the prebuilt layer/substrate hence the slices can be planar or non-planar. Consider the case shown in Figure 6a, the first step is to identify the features as per their feasible build direction. One can notice that the red inside the cylindrical feature (in red color) can be easily manufactured by using 3-axis slicing method. Figure 6b shows the slicing of the cylindrical part and Figure 6c shows the outer intersecting contours in an intermediate slice. After the realization of inside cylindrical feature on 3-axis, the outer feature needs to be realized on its periphery. For that, the base (which is cylindrical in this case) will be offset by the required layer thickness as shown in Figure 6d. One can notice now that the each slice is a cylindrical surface with a different radius equal to the offset value. Figure 6e show an intermediate non-planar slice with the intersecting contours. Similar to the previous method the material can be deposited along these contours and then the inside area can be filled as shown in Figure 6f.

All three described methods (3-axis adaptive slicing, 5-axis slicing, and non-planar conformal slicing) has been demonstrated as a case study by manufacturing an impeller. The results obtained for this case study has been discussed in the next section.

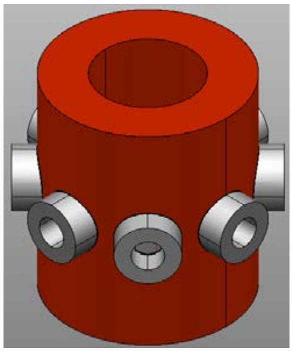
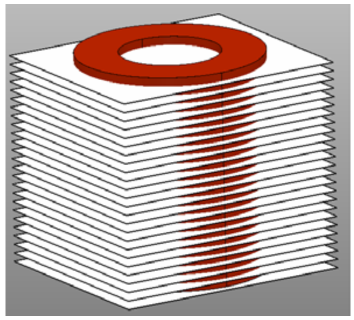
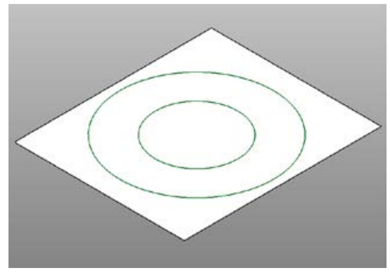
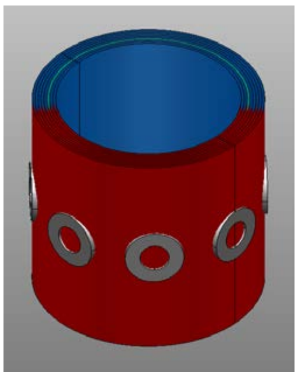
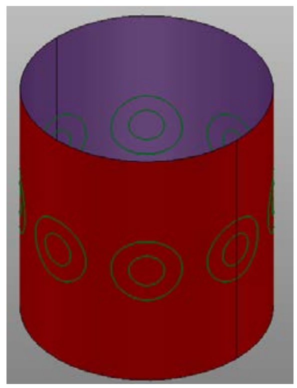
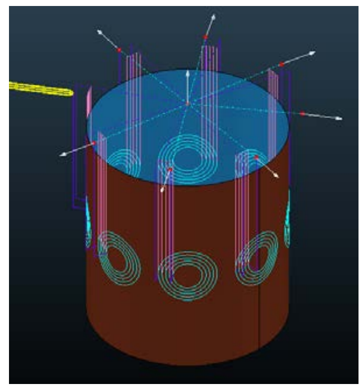
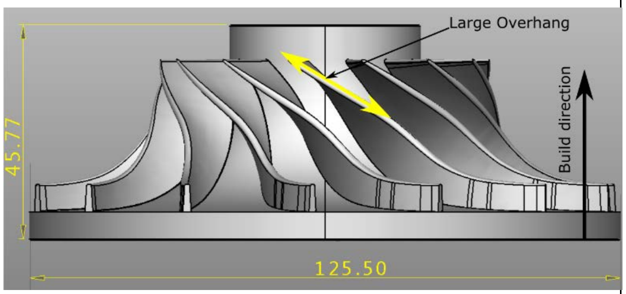
		
(a) CAD model of the component	**(b)** Slicing of the inside cylindrical feature	**(c)** An intermediate slice with intersecting contours
		
(d) Slicing of the outer feature with non-planar cylindrical slices	**(e)** An intermediate non-planar slice with the intersecting contours	**(f)** Toolpath generation for the material deposition in the non-planar slice

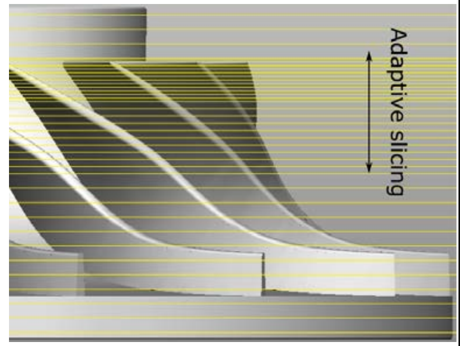
Figure 6: Feature-based non-planar conformal slicing method

Results and Discussion

An impeller has been manufactured using HLM process as a case study by the above discussed three methods. Figure 7a shows the CAD model of an impeller to be manufactured by using adaptive 3-axis slicing method. One can observe that in the build direction, on the top of the impeller there is a large overhanging feature. Hence an adaptive slicing will be required to keep the constant overhang. The variable layer thickness from 2mm to 0.5mm was obtained by an in-situ face milling operation. Figure 7b shows the adaptive slicing of the impeller with the region of smaller layer thickness. Figure 7c show the intermediate stage of the impeller after deposition of few constant thickness layers (2mm). The final near-net shape obtained by the deposition is shown in Figure 7d. It was observed that if the layer thickness becomes very small (0.5 mm) then during the next layer deposition it starts melting and hence the material starts falling down. One can observe the rounded edges of the impeller in Figure 7d. This method could not produce a very accurate near-net shape of the impeller. Hence another method, 5-axis slicing was used which is described in the following paragraph.



(a) CAD model of the scaled impeller



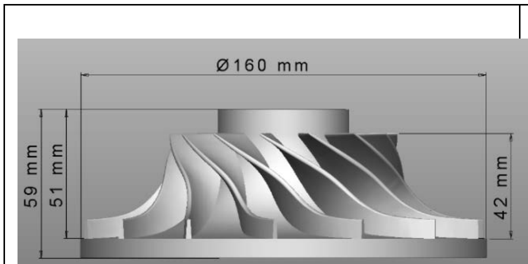
(b) Adaptive slicing of the impeller

(c) Deposition of impeller an intermediate slice

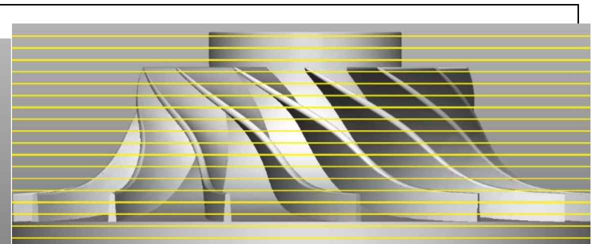
(d) Final near-net shape

Figure 7: Realization of the impeller using 3-axis adaptive slicing

Figure 8a shows the CAD model of the impeller to be manufactured by 5-axis planar slicing. As discussed earlier the planar slices are done as shown in Figure 8b. The intersection between each layer and component was obtained with required torch vector for the overhanging feature. First, the outer contours are deposited using 5-axis kinematics by tilting the base plate accordingly. Figure 8c shows the deposition of the outer contour in an intermediate slice. Then the inside area is filled using a 3-axis kinematics, see Figure 8d. Repeating these steps for all the slices will result in a near-net shape of the impeller as shown in Figure 8e. Compare to the previously deposited near-net shape by 3-axis slicing method, this near-net shape is found to be more accurate. The near-net shape is then final milled and the finished component is shown in Figure 8f. The final product's weight is 1.015 Kg while the weight of near-net shape is 1.826 Kg. The weight of the bounding cylinder of 170mm x 80mm is 4.901 Kg. Hence the material saved as compared to the purely subtractive process is 4.901 - 1.826 = 3.075 Kg. The time was also recorded throughout the deposition process and it was found that it took approximately 4hr to realize the near-net shape of the impeller.



(a) CAD model of the impeller



(b) Planar slicing of the impeller

(c) Outer contour deposition of an intermediate slice

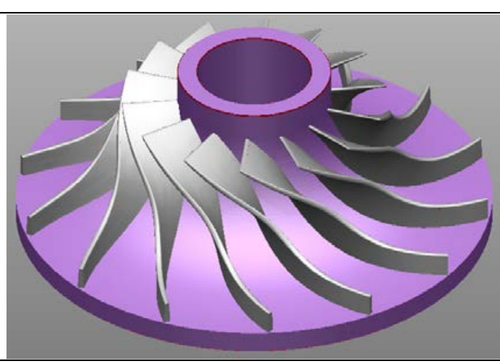
(d) Area filling of an intermediate slice

(e) Final Near-net shape

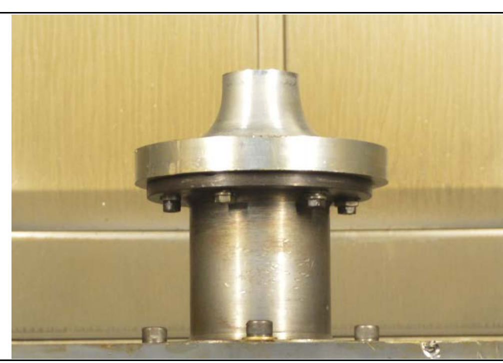
(f) Final finished component

Figure 8: Realization of the impeller using 5-axis planar slicing

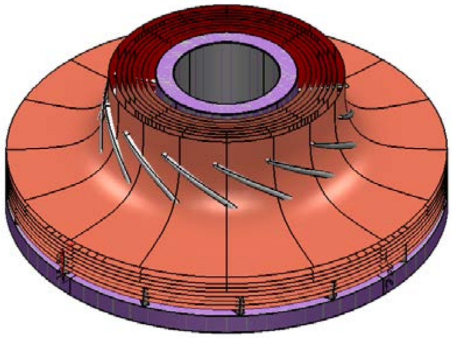
To further improve the near-net shape of the impeller obtained by the planar 5-axis slicing method, a non-planar conformal slicing method was used. As described earlier, first the features are identified based on their buildability in the different build direction. Figure 9a shows the decomposed CAD model of the same impeller into two features viz; (a) inside the hub and (b) blades. The inside hub can be manufactured using the 3-axis kinematics, see Figure 9b. After deposition of inside hub, its top surface was considered to be the first slice for the blade deposition. The hub surface is then offset by 1mm up to the radial height of the blades, Figure 9c shows all the non-planar slices for the realization of the blades on the hub. An intermediate slice with deposition toolpath and it actual deposition is shown in Figure 9d and 9e respectively. Depositing the blades on each offset non-planar slice will result in the near-net shape of the impeller shown in Figure 9f. One can clearly observe that this near-net shape is much closer to the CAD than the one created by the last method of 5-axis planar slicing.



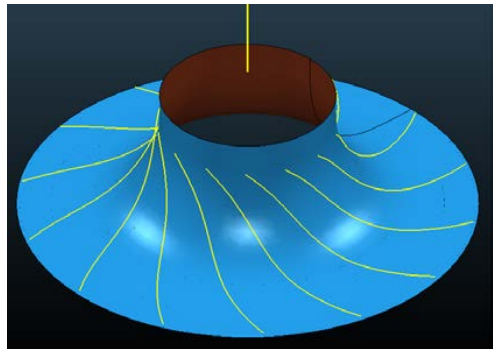
(a) Feature identification



(b) Deposition of hub



(c) Non-planar slicing for the blade deposition



(d) Deposition path in an intermediate slice

(e) Deposition the intermediate layer of blades

(f) Near-net shape of the impeller

Figure 9: Realization of the impeller using 5-axis non-planar slicing

Conclusions

For *Additive Manufacturing (AM)* process three slicing methods have been described in this work, viz; 3-axis adaptive slicing method, 5-axis planar slicing method, and 5-axis non-planar slicing method. Each method has been explained with the help of a suitable example. An impeller was manufactured using *Hybrid Layered Manufacturing (HLM)* process, as a case study to demonstrate the capability of the proposed slicing methods. The near-net shape produced by 5-axis planar slicing method has the consistent deposition on each layer without any toolpath error. As compared to conventional machining it has been found that for this case study the saving in material is approximately 63%. The near-net shape produced by the 5-axis non-planar slicing method is found to be the best among all three methods. The developed slicing methods are not only limited to HLM process but can be used for other AM process such as SLS, FDM etc. The parameters that controls the adaptive slicing has to be investigated in future work.

References

1. P. Singh and D. Dutta, 2001, "Multi-Direction Slicing for Layered Manufacturing," Journal of Computing and Information Science in Engineering, 1(2), pp. 129 - 142.
2. J. Zhang, 2004, "Adaptive Slicing for a Multi-Axis Laser Aided Manufacturing Process," ASME Journal of Mechanical Design, 126(2), pp. 254 - 261.

3. R. Sundaram and J. Choi, 2004, "A Slicing Procedure for 5-Axis LaserAided DMD Process," ASME Journal of Manufacturing Science and Engineering, 126(3), pp. 632 - 636.
4. J. Ruan, K. Eiamsa-ard and F. W. Liou, 2005, "Automatic Process Planning and Toolpath Generation of a Multiaxis Hybrid", Journal of Manufacturing Processes, 7(1), pp. 57 - 68.
5. J. Ruan, T. E. Sparks, A. Panackal, F. W. Liou, K. Eiamsa-ard, K. Slattery, H.-N. Chou, and M. Kinsella, 2007, "Automated Slicing for a Multiaxis Metal Deposition System," ASME Journal of Manufacturing Science and Engineering, Vol. 129(2), pp. 303 - 310.
6. F. Liou, K. Slattery, M. Kinsella, J. Newkirk, H. N. Chou, and R. Landers, 2007, "Applications of a hybrid manufacturing process for fabrication of metallic structures," Rapid Prototyping Journal, 13(4), pp. 236 - 244.
7. L. Ren, T. Sparks, J. Ruan, and F. Liou, 2008, "Process planning strategies for solid freeform fabrication of metal parts," Journal of Manufacturing System, 27(4), pp. 158 - 165.
8. P. Singh and D. Dutta, 2008, "Offset Slices for Multidirection Layered Deposition," ASME Journal of Manufacturing Science and Engineering, 130(1), pp. 011011 - 12.
9. J. Ruan, L. Tang, F. W. Liou, and R. G. Landers, 2010, "Direct Three-Dimensional Layer Metal Deposition," ASME Journal of Manufacturing Science and Engineering, 132(6), pp. 064502 - 6.
10. L. Ren, T. Sparks, J. Ruan, and F. Liou, 2010, “Integrated Process Planning for a Multiaxis Hybrid Manufacturing System,” ASME Journal of Manufacturing Science and Engineering, 132(2), pp. 021006 - 7.
11. J. Zhang and F. Liou, 2013, "Multi-Axis Planning of a Hybrid Material Deposition and Removal Combined Process," Journal of Machinery Manufacturing and Automation, 2(3), pp. 46 - 57.
12. A. Calleja, I. Tabernero, A. Fernández, A. Celaya, A. Lamikiz and L. N. López de Lacalle, 2014, "Improvement Of Strategies and Parameters for Multi-Axis Laser Cladding Operations," Optics and Lasers in Engineering, 56, 113 - 120.
13. S. Kapil, P. Joshi, H. V. Yagani, D. Rana, P. M. Kulkarni, R. Kumar, K. P. Karunakaran, 2016, "Optimal Space Filling for Additive Manufacturing," Rapid Prototyping Journal, 22(4), 660-675.