Five-Axis Freeform Fabrication of Thermoplastic Parts via SWIFT

Tushar R. Mahale, James B. Taylor, Denis R. Cormier
Department of Industrial Engineering, North Carolina State University, Raleigh, NC 27695

Abstract

Current Rapid Prototyping (RP) & Layered Manufacturing (LM) techniques are based on controlled, precise additive manufacturing methods. These techniques suffer from problems associated with stair stepping, loss of accuracy in the z-direction due to limitations on the slice thickness and their build speeds which prevent them from being “rapid”. Proposed here, is a method, which utilizes a freeform fabrication technique, coupled with the advantages and precision of five axis machining for contoured edge generation. A new technique for the generation of solid thermoplastic parts (ABS, Polystyrene, etc) will be introduced. The proposed process will incorporate adaptive slicing for the generation of five-axis CNC code, and a sub-layer machining technique for use of uniform layer thickness will be outlined. A novel 5-axis configuration will be proposed. The proposed process will decrease, drastically, the time required for part production when compared to current commercial technologies.

Introduction

Rapid Prototyping (RP) has become synonymous with precision, layered manufacturing (LM). Though a fast method for developing prototypes, most of the commercially available processes have relatively high costs associated with them. These costs account for the fixed cost of equipment, and equally high variable cost of spares and consumables.

LM processes are currently evolving from general rapid prototyping techniques to processes that provide industry specific manufacturing solutions (Karunakarn, 1999). Current markets have been exhibiting trends toward mass customization and LM will certainly have a place in the market. In spite of all the advances, almost all RP & LM processes still suffer from certain inherent deficiencies such as, stair stepping, low accuracy in comparison to machined parts, poor surface finish before post-processing, limitations on build materials, directional structural properties, and a non-homogeneous nature of the manufactured parts (Mahale, 1999, Tata, 1998).

SWIFT

A new process, Solvent Welding Freeform Fabrication Technique (SWIFT) involves the solvent welding of thermoplastic layers and the machining of layer contours (Taylor, 2000a). The process is being developed to meet the demands for generating low cost, high precision large to very large parts having fairly complex details. An attempt has been made to counter some of the limitations of layered manufacturing processes by addressing speed, accuracy, strength and cost issues.

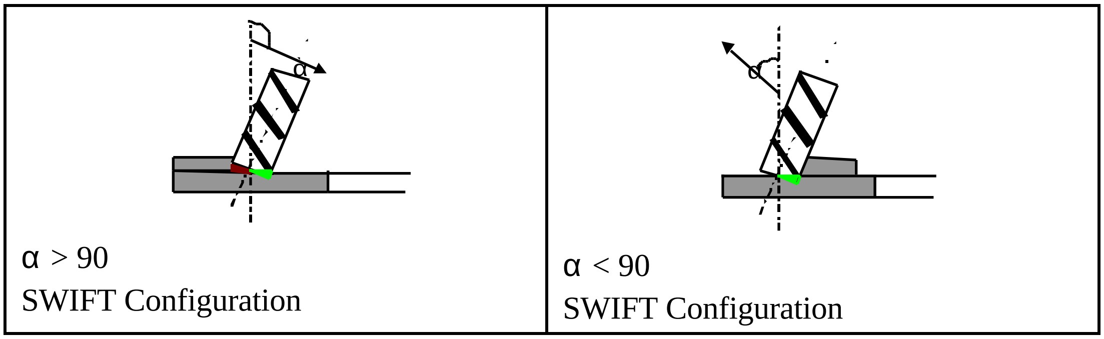
In SWIFT, solvent weldable thermoplastic sheets of uniform layer thickness (sheets with variable layer thickness can also be used) are cut into a machine loadable size (currently a maximum size of 7 inch x 10 inch can be accepted by the prototype machine). A suitable mechanism is used to automatically load the sheets onto the machine build platform. As the sheet is being passed through the loading mechanism, a uniform layer of solvent is applied to the bottom of the sheet. The entire bottom surface of the sheet is coated with the solvent when the sheet is brought over the build platform and then pressed over the previous layer by means of a platen. The platen is held over the sheet in the same position for about 5-10 seconds to allow chemical bonds to form at the interface of the sheets, after which it is retracted. This assures a solid welding between the two sheets and the evaporation or absorption of the excessive solvent. On areas where bonding is not desired, a solvent mask can be applied. This can be the case especially on horizontal part surfaces. Once the platen is retracted, a face mill sizes the sheet to the required layer thickness. The face mill is retracted, and an end mill is loaded onto the spindle. At this stage, two more axes of control of the SWIFT machine are utilized (5-axis machining) to achieve the desired sloping surfaces on the edges of the contours of slices. The end mill machines the edge contours for the current slice. The whole process is repeated for the remaining layers. The SWIFT part is obtained by removing the build block from the build platform followed by the removal of the support structures. An alternative method for support stock removal would be required in the case of parts exhibiting a “bird cage” structure.

SWIFT Machine Configuration

Conventional 5-axis machining centers consist of fully articulated heads i.e. two rotary axis are mounted on the spindle head and the three linear axes are distributed to the machine table and spindle head. LM involves the machining of one single, relatively thin layer at a time, and this layer is always positioned at the top of the part to be machined. Thus the cutting position of the bottom face of an end mill for cutting the edge contours would remain constant in the z-direction. This suggests the possibility of utilizing only four simultaneously controlled axes during the process of edge contoured milling instead of the simultaneous 5-axis control as used in conventional 5-axis machining techniques (Ng, 1998, Wang, 1999). Such a machine would be a 4-_-axis machine rather than 5-axis.

The proposed machine configuration calls for the build platform to be mounted on a rotary table so as to attain rotary motion along the Z-axis (C-axis). The rotary table would also have a linear motion along the Z-axis for between-layer positioning. The linear motion along the X & Y axes can be achieved through the standard motion of the spindle head. A unique configuration for the 5th axis (A-axis) has been proposed to specifically cater to the needs of LM processes. The rotary motion of the A-axis is attained by pivoting the spindle about the Y axis, with the center of rotation coinciding with the bottom surface of the layer that is being machined. This greatly reduces the computational overhead associated with conventional 5-axis machining where the A-axis is pivoted above the cutting tool requiring the calculation of the simultaneous X, Y, and Z movement to be imparted to the table by way of compensation. It should be noted, the assembly for generating linear traverse along the y-axis is mounted on the A-axis, thus any movement to the A-axis results in a similar motion.

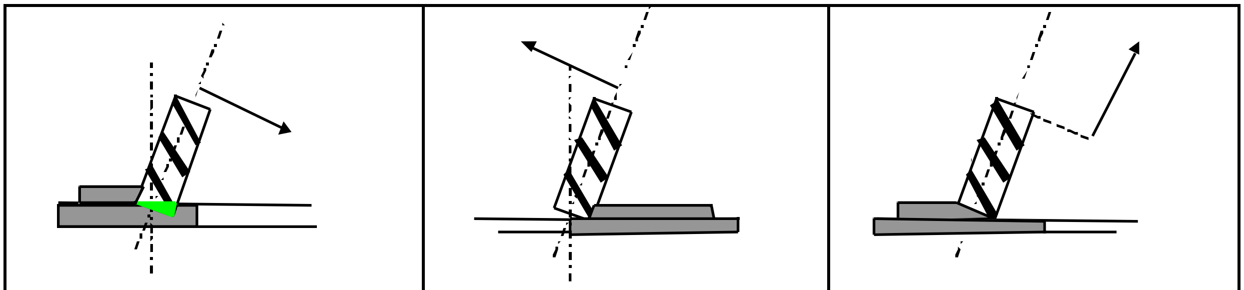
As seen in the figure below, due to the finite diameter of the tool, the 4-_-axis configuration could result in the previous layer being gouged. The nature of pivoting for the A and C-axis would also limit the tool from completely cutting the down facing surfaces. A relation between the permitted deviation in the part dimensions, layer thickness, cutter diameter and the angle of the A-axis can help generate acceptable parts. Considering these limitations, the proposed configuration would be effective primarily for the manufacture of parts using large layer thickness (preferably using a small cutter diameter).



🟩 Gouged Region 🟥 Uncut Region

Figure 1 – Gouged and uncut regions in contoured edge generation

An alternative 5-axis configuration might partially help to solve the problem presented above. The 4-_-axis configuration presented above involves a setup where the A-axis moves tangential to the bottom surface of the machined layer. In an alternative 5-axis configuration, the axis of rotation of the A-axis is moved to the intersection of the bottom surface of the tool and the tool's axis of rotation. The proposed 5-axis configuration eliminates uncut regions, but increases the gouged region during the machining of down facing facets. The possibility of cutting into the previous layer while machining down facing part edges exists when the previous layer extends beyond the bottom of the top layer. Though a better configuration, it would be difficult to machine downward facing facets which are at a large angle with the z-axis. The figure below shows the proposed 5-axis configuration being utilized to machine upward facing facets. The face of the tool is used to machine facets where the angle made by the facet with the z-axis is less than 45 degrees. In case where the angle between the facet and the z-axis is greater than 45 degrees, the bottom surface of the tool is used for machining the contoured edge. As is seen in the figure, this technique eliminates the gouged regions. It can be noted that in spite of utilizing simultaneous control of 5 axes, the amount of compensatory motion along the z-axis while machining a single layer is minimized.

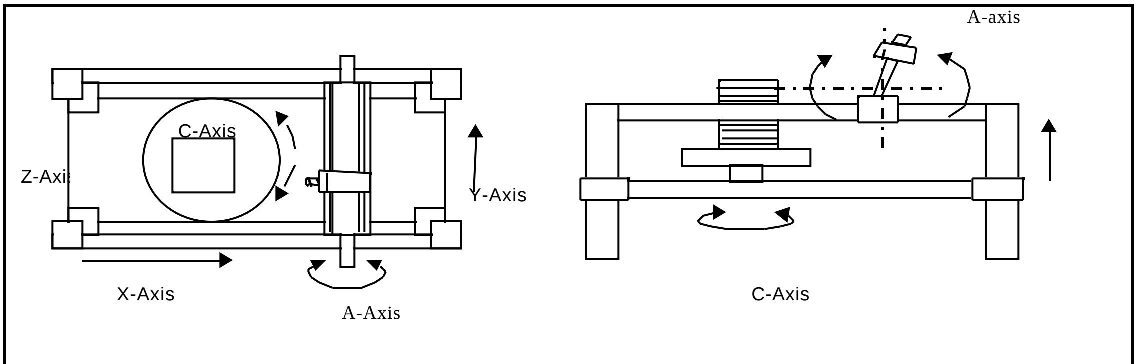


Machining down facing facets 5-Axis Configuration

A-axis tilt between 0-45 degrees

A-axis tilt > 45 degrees

Figure 2 – Alternate Edge contour generation



Top View

Front View

Figure 3 – New 5-axis machine configuration

Adaptive Slicing of STL

The name Layered Manufacturing suggests manufacturing by means of stacking laminated layers (Dolenc, 1995). To generate the necessary data to conduct the LM operation, the CAD model of a part is intersected with parallel planes. The details generated through the intersection of a plane with the part contribute to the topographical details for that layer (Kulkarni, 1997). The operating cost of LM processes is a function of processing time, and the processing time is largely dependent on the number of layers required to build a part. One of the methods of decreasing the operation cost is to decrease the number of layers and hence the time required for manufacturing a part. The decrease in the number of layers is possible only by increasing the slice thickness. An increase in slice thickness (uniform slice thickness) over the entire part may result in the loss of accuracy along the Z-direction and substantial increase in stair stepping. The accuracy of a part can be maintained by adaptively selecting the layer thickness for individual layers as the part is being built. Though an effective method, zeroth order adaptive slicing can reduce but not eliminate instances of stair stepping. First order adaptive slicing (i.e. adaptively slicing the part for the generation of sloping surfaces from edge boundaries) is one of the best alternatives for approximating the surface of the STL model; thus minimizing stair stepping.

Sub-Layer Machining

The SWIFT process involves the generation of layers through contour machining, thus the processing time per layer is related to the cutting speed and the length of the perimeter of the layer, as well as the overhead to apply the layer and size it. Face milling and sizing is conducted for each layer to maintain the accuracy of the part in the Z-direction as well as to assure a clean surface at the interface between two layers. Thin layers generated after adaptively slicing a part involve large cuts during the sizing, leading to the waste of raw material and an increase in processing time. An additional enhancement to this process would be to recognize the possibility of generating multiple thin layers from a base stock of higher thickness. This could play a big role in reducing the processing time, by greatly reducing the overhead time required for a group of sub-layers. In essence, the process of sub-layer machining treats a single thick layer of thermoplastic sheet to be composed of multiple layers of the sliced part. The result is that the time required for face milling (γ) for the 'n' sub-layers within the single thermoplastic sheet is reduced to γ from the original $n*\gamma$. Sub-layer machining is possible for layers that exhibit all up facing facets, i.e. layers consisting of facets whose *k* component of the normal is greater than zero (the capability of slicing software is currently limited to slicing along the Z-direction). This is simply because of the fact that it would be impossible to cut a bottom most sub-layer within a thermoplastic sheet without cutting into adjoining sub-layers.

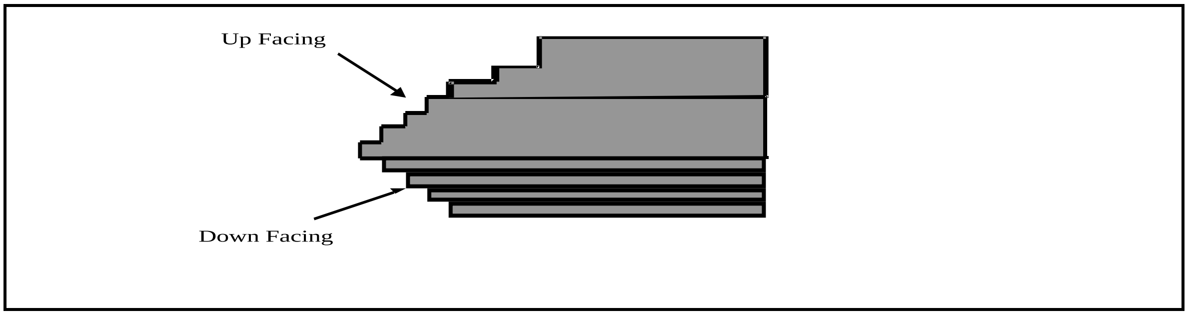


Figure 4 – Up and down facing sub-layer 3-axis edge contours

Volumetric Adaptive Slicing

In a 5-axis process, the use of 1st order adaptive slicing leaves us with the possibility of the occurrence of only the layering error (Hope, 1997a, Hope, 1997b, DeJager, 1996). Layering error can be measured in terms of volume, Ψ, as it represents the region of the layer which has not been accurately generated i.e. it represents an uncut or gouged region.

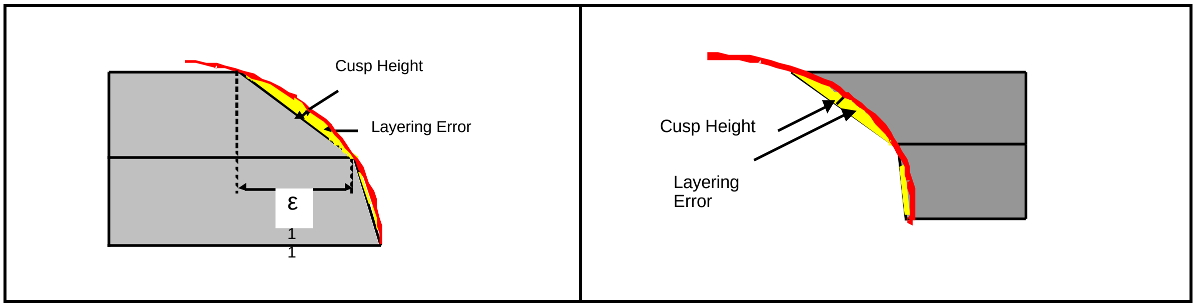


Figure 5 – Layering error in 5-axis edge generation

Earlier attempts at measuring layering error (Taylor, 2000b, Suh, 1994), involved approximating the volume Ψ by determining the cusp height, ξ, or by trying to determine the maximum difference in the layer plane, ε. The value of ε is considered to be a measure of layering error whereas the cusp height was considered to be a representation of the surface roughness. These measures are helpful when using the 0th order adaptive slicing. Layering error will not be exhibited when using 1st order adaptive slicing to slice a highly slanted planar surface, in spite of a large value of ε. The 1st order adaptive slicing technique might result in a non-zero cusp height; but this may not necessarily be a measure of surface roughness, as contoured edge generation tends to smooth the surface and eliminate the stair stepping.

As the prime objective of adaptive slicing is to reduce the layering error, thus, one of the criteria for adaptive slicing should be to actually measure the layering error (volume). The process begins by creating the first two slices of the part, beginning bottom up. The first slice is taken at Z=0 and the second slice is taken at the maximum possible slice thickness.

The perimeter P_j of the layer (cross-section) where j = top or bottom of the layer are calculated where

$$P_j = \sum_{i=1}^{n} |\vec{v}_i|$$

$\vec{v}_i \equiv$ Vector i which is a part of the loop

$n \equiv$ Total number of vectors in a loop

The area of the top and bottom surface of the layer is calculated as

$$A_j = \left| \sum_{i=1}^{n} \left[\left(X_{2i} - X_{1i} \right) * \left(\frac{Y_{1i} + Y_{2i}}{2} \right) \right] \right|$$

$(X_{1i}, Y_{1i}, Z_{1i}) \equiv$ Starting point of vector $\vec{v}_i$

$(X_{2i}, Y_{2i}, Z_{2i}) \equiv$ Ending point of vector $\vec{v}_i$

Note: by definition the value of Z remains constant for a given loop.

The volume generated by the contoured edge is estimated as

$$V_{con} = \left(\frac{A_{top} + A_{bottom}}{2} \right) * h$$

$h \equiv$ Maximum possible slice thickness

The actual volume of the layer (on the basis of the STL file) is given by

$$V_{actual} = \left| \sum_{a=1}^{p} q_a (\vec{M}_a \cdot \vec{N}_a) \right|$$

where, q_a ≡ Area of facet ‘a’ (facet consists of triangles, quadrilaterals and the upper and lower cross section of the layer due to initial slicing)

$\vec{M}_a$ ≡ Vertical vector from plane Z = 0 to the middle point (centroid) of facet a

$\vec{N}_a$ ≡ Unit vector representing the direction of normal of facet a

The layering error criterion ≡ $\varpi = \left| \left[V_{actual} - (A_{\min} * h) \right] - \left[V_{con} - (A_{\min} * h) \right] / P_{\max} \right|$

N.B. The layering error criterion (volumetric technique) does not evaluate the surface of a layer in a localized fashion, but is a normalized volumetric error per unit length of perimeter.

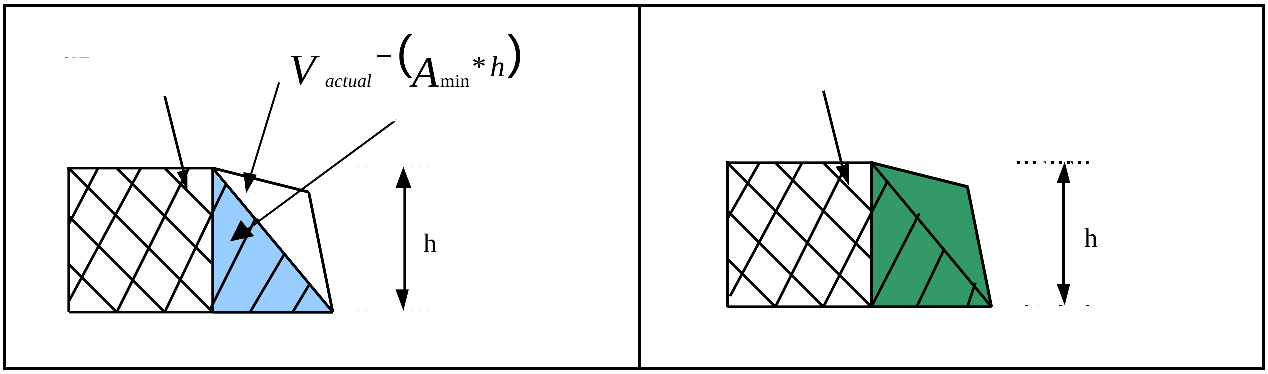


Figure 6 – Layering error comparisons

As seen from the figure, the expression $\left| \quad \right|$ represents the layering error over the entire layer in terms of volume. Dividing this value by $P_{\min}$ gives us a pessimistic value of the layering error per unit length of the perimeter. A user defined look up table helps the system to decide upon the number of layers the given layer is to be subdivided into. A sub-layer machining operation coupled with the volumetric slicing technique could be of great help in reducing the processing time, while simultaneously maintaining part accuracy.

Conclusion

This paper has presented some of the results of research and development activities regarding rapid prototyping in general and the SWIFT process in particular. Software and hardware enhancements to the process have recently added 5-axis sub-layer slicing. Software for 1st order adaptive slicing and machining capabilities and software for 5-axis contoured edge slicing has been developed and tested in a virtual environment. This enables the system to produce adaptively sliced, contoured edge parts using a uniform sheet thickness for the build material. A new configuration for a desktop 5-axis milling machine specifically designed for the SWIFT application has been proposed here and is currently under development. Future work will include building and testing the 5-axis machine and software enhancements to account for more difficult-to-build parts that include features such as “floating islands”, further reduction of processing time and other special features of historical importance to rapid prototyping development. On a 3-axis test bed, the process has proven its capability of producing, high strength thermoplastic parts. The SWIFT process has demonstrated advantages in low fixed and variable costs, part strength, part accuracy, process speed, and adaptability to advanced methods. At the present time the process is limited to thermoplastic parts and a rotational cutter of finite diameter serves as a limit to fine feature replication (though cutters of 0.031” have been successfully used).

Figure 7 – SWIFT part with sublayer 3-axis machining detail, sublayer thickness of 0.012”.

References

Dolenc, A., Makela, I., “Slicing Procedures for Layered Manufacturing Techniques”, Computer Aided Design, Vol. 26 No.2, 1995.

De Jager, P. J., “Using Slanted and ruled layers for rapid prototyping”, in Dickens P. (Ed.), Proceedings of the 5th European Conference on Rapid Prototyping and Manufacturing, Helsinki, 1996.

Hope, R.L., Jacobs, P.A. et al, “Rapid Prototyping with Sloping Surfaces”, Rapid Prototyping Journal, Vol.3 No.1, 1997

Hope, R.L., Roth, R.N. et al, “Adaptive Slicing with Sloping Layer Surfaces”, Rapid Prototyping Journal, Vol.3 No.3, 1997

Karunakarn, K.P., Bapat, V.P., Mahale, T.R., et al, “Rapid Prototyping & Tooling-An Overview”, IDC, IIT-Bombay Press, 1999.

Kulkarni, P., Dutta, D., “An Accurate Slicing Procedure for Layered Manufacturing”, Computer Aided Design, Vol. 28, No.9, 1997.

Mahale, T. R., Bapat, V.P., “Rapid Prototyping & Design”, Intl. Conference on Strategic Manufacturing for Competitive Advantage; Confederation of Indian Industries, Mumbai, August-1999

Ng, P., Fang, W. et al, “Motion Compensation for Five Axis Rapid Prototyping System”, Rapid Prototyping Jounal, Vol. 4 No. 2, 1998

Suh, Y., Wozny, M., “Adaptive Slicing for Solid Freeform Fabrication Processes”, Proceedings of the Solid Freeform Fabrication Conference (1994), The University of Texas, Austin

Tata, K., Fadel, G. et al, “Efficient Slicing for layered manufacturing”, Rapid Prototyping Journal, Vol.4 No.4, 1998

Taylor, J., Cormier, D., “Rapid Prototyping via a Solvent Welding Freeform Fabrication Technique”, Proceedings of the Industrial Engineering Research Conference 2000, May 21-24, 2000, Cleveland OH, IIE Press.

Taylor, J., Cormier, D. et al, “Contoured Edge Slice Generation in Rapid Prototyping via 5-Axis Machining”, Proceedings of 10th International Conference on Flexible Automation and Intelligent Manufacturing, College Park Maryland, June 26-28, 2000, Vol. 1, pp. 183-192.

Wang, Y., Tang, X., “Five Axis NC Machining of Sculptured Surfaces”, International Journal of Advanced Manufacturing Technology (1999) 15:7, 14