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Adaptive crosshatch approach for the laminated object manufacturing (LOM) process

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The waste material removal process of laminated object manufacturing (LOM), so-called 'decubing', is a labour-intensive and time-consuming work resulting from the commonly used uniform crosshatch setting. An adaptive crosshatch approach to improve working efficiency and alleviate the effort involved in the decubing process is developed. The working region is divided into two portions, the inner region and the outer region, by the proposed rectangle and original contour offset approaches. The fine crosshatch pattern is designated to the inner region based on the shape of the cross-section contour, and the rules to select crosshatches for different shapes are given. The outer region has a coarse crosshatch pattern, and it is an integer multiple of that of the inner region. The brick-layered effect in the overlap zone of the waste material is eliminated by the projection method. Experiments show that with the adaptive crosshatch approach there are four major advantages: saving laser power consumption, protecting the part from damage, improving machining efficiency and easier decubing.

1. Introduction

Rapid Prototyping is a new class of automated fabrication processes that allows the construction of 3D objects from solid or surface CAD files by horizontally sectioning the desired model into slices and then constructing each cross-section from the bottom up one layer at a time. The major advantage of rapid prototyping is to reduce the time from design to manufacture. With rapid development of this technology, it is predictable that the traditional labour-intensive and time-consuming model-building process will soon be superseded.

Laminated Object Manufacturing (LOM) is one of the most popular rapid prototyping techniques in terms of speed and cost effectiveness. The process is described in figure 1. It uses the 'bond-then-cut' principle (Feygin 1994, Thomas 1996). A sheet is laminated to the previously laid and bonded layers by a hot roller. The roller applies heat and pressure as it rolls over the sheet, which has a thin layer of thermoplastic adhesive on the down-facing surface (Pak and Nisnevich 1994, Sonmez and Halh 1998). After the new layer is bonded, a focused beam of a CO_2 laser incises the outline of the part. Laser power is adjusted to cut through only one layer of lamination. The unused material is left in place, however, diced with crosshatch into small pieces called 'tiles' for easy removal. The iterative process of bonding and laser cutting is repeated until the construction of the final layer is completed. Once all layers have been laminated and cut, excess material is removed to expose the finished part. Procedures of decubing are given in figure 2. First, the laminated stack is

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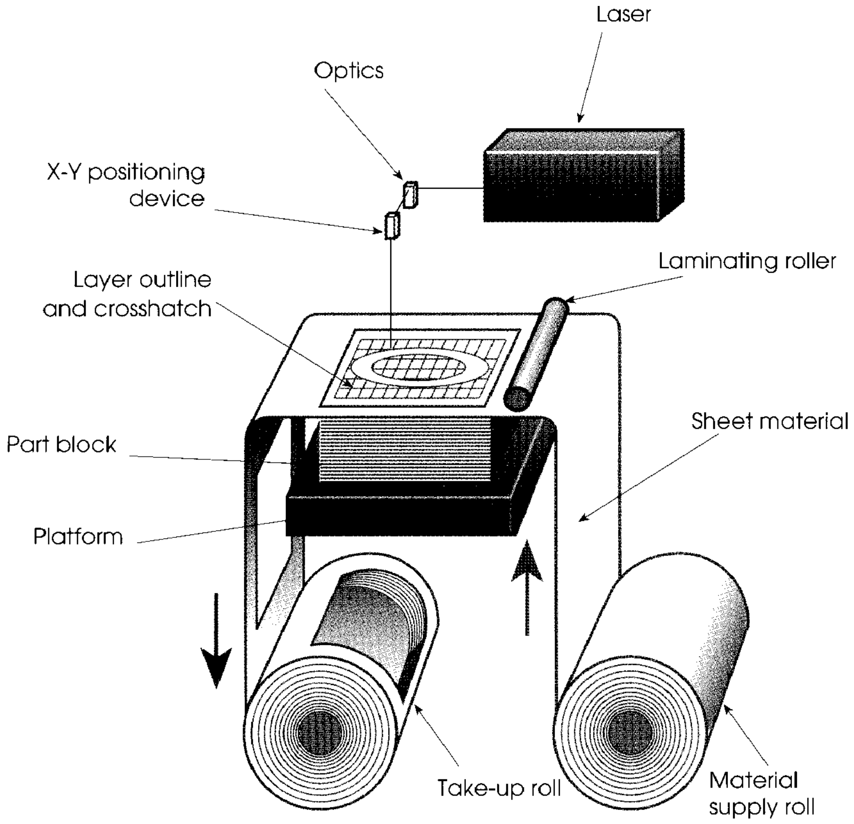
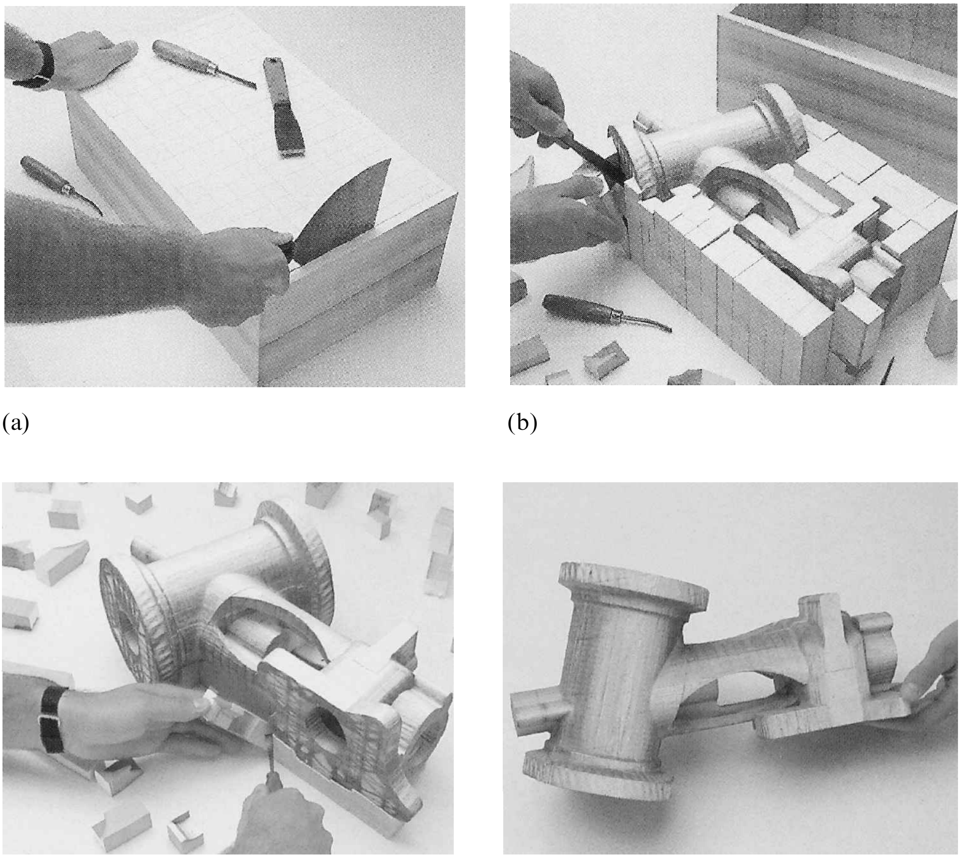


Figure 1. LOM process (Cohen 1991). Courtesy Helisys, Inc.

removed from the platform of the machine. The surrounding wall is then lifted off to expose cubes of excess material. This is followed by manually separating the cubes from the part's surface and obtaining the desired part.

Despite the advantages of the LOM process, some problems are yet to be overcome. One of the major difficulties encountered in the current LOM practice is the operation with the material removal process, also called 'decubing' (Cohen 1991). The scrap material is not only as strong as the part itself, but also adheres to the part. Therefore, to ensure that only waste material is removed and delicate sections of the part are not fractured, the clean up has to be handled with care. That is to say, the decubing process is time-consuming, labour-intensive and experience needed to do the work.

Generally speaking, there are two factors—the location and size of the waste material—that would make the decubing process more difficult. In terms of locations, if the waste material was trapped within the walls, internal cavities with restricted access, blind holes, etc., it would be difficult to be removed. In terms of sizes, since the bonding strength is proportional to the size of bonding area, if the crosshatch chunks were big and strong, they would be difficult to be separated from the part (Klosterman *et al.* 1997a, b). It is therefore suggested that the size of crosshatch should be as small as possible. If the crosshatches are made smaller (for easier removal), the machining time will increase. Therefore deciding an optimal crosshatch



(a) (b)

(c) (d)

Figure 2. Decubing process of an LOM part: (a) laminated stack is removed from the machine's platform; (b) surrounding wall is lifted off the part to expose cubes of excess material; (c) cubes are separated from the part's surface; (d) part is done. Courtesy Helisys, Inc.

value is a dilemma. Table 1 shows the general processes involved in LOM. It is readily understood that the amount of time spent in crosshatching and decubing for typical parts dominates the total fabrication time.

A concept that used three different crosshatch patterns—fine, medium and coarse—to reduce the crosshatch was proposed (Feygin and Pak 1997, Feygin and Pak 1999). The proposed crosshatch patterns were determined by *x*–*y* section of

Process	Time (%)
Crosshatch machining	35
Part's contour machining	25
Decubing	40

Table 1. General processes for the LOM.

sliced part only. However, the variation along z-axis was not taken into account. The machining time would decrease, however the decubing time would increase and the waste material was hard to separate from the retraction of the part under the situation. Therefore, the research of crosshatch improvement is worthy of being developed.

To solve the problems stated above, a new adaptive crosshatch approach to reduce the time for decubing and improve machining efficiency is proposed. The working region is divided into two portions with the approach, the inner and outer regions, which have the fine and coarse crosshatch patterns, respectively. Because the size of crosshatch of the outer region is larger than that of the inner region, the waste crosshatch chunks in the outer region are more easily removed and the machining time is decreased. In addition, because the crosshatch chunks in the inner region are relatively tiny, it reduces the possibility to damage the part when the waste material is being removed.

In this paper, a part is tested with the adaptive crosshatch approach and the advantages of saving power consumption, saving machining and decubing time and protection of the part from damage are demonstrated.

2. Criteria for the adaptive crosshatch approach

The strategy used in the adaptive crosshatch approach is to eliminate the excessive crosshatches. The adaptive crosshatch approach is favourable when the volume ratio of waste material to part is 1 (equation 1): sculpture parts, thin-wall parts and delicate parts, for example. In other words, the more the waste material, the more effective in the use of the adaptive crosshatch approach. Equation (1) can be used as a criteria rule as to whether the adaptive crosshatch approach should be applied:

$$\text{Volume of waste material/volume of part material} \geq 100\% . \tag{1}$$

Note that the 'block' of part is formed according to its minimum and maximum coordinate of the x-, y- and z-axes. After all layers have been processed by the LOM machine, the result is a part imbedded within a block of waste material. That is, the block minus the volume of part is equal to the volume of waste material.

3. Adaptive crosshatch approach

The adaptive crosshatch approach is composed of several steps, which will be described as follows. First, the suitable offset section is determined. There are two approaches, 'rectangle offset approach' and 'original contour offset approach', for determining the offset section based on the geometry of the part. Once it is determined, the working region is divided into two portions: the outer region, between the contour of the offset section and the wall, and the inner region, between the contour of part and contour of the offset section. The inner region uses the fine crosshatch and the outer region uses the coarse crosshatch, which is an integer multiple of that of the inner region. Then, the overlap zone, which needs fine crosshatch, is calculated with the 'projection method'.

3.1. *Determination of offset section*

The 'rectangle offset approach' is applied if the part is concave shaped. From experience, it is learnt that if the inner region is a rectangle, the waste material of the outer region would be easier to be removed. The approach to decide the rectangle region is explained as follows. When the 3D model is sliced into layers, the maximum and the minimum coordinates along the x- and y-axes of each layer i are obtained. With these maximum and minimum coordinates, the coordinates of rectangle's corners—shown as $(a^i_{\min}, b^i_{\min})$, $(a^i_{\max}, b^i_{\max})$ in figure 3a—can therefore be decided. That is to say, the slice of the part is enclosed by a rectangle and the region between the contour of the part and the boundary of the rectangle is the 'offset section' mentioned above. The advantage of the rectangle offset approach is that it is less likely to generate imbedded parts of waste material, which are often difficult to be removed. Besides, the rectangle offset approach also saves times in calculating work.

On the other hand, if the part is convex-shaped or composed of thin-wall, islands, pockets, etc., the 'original contour offset approach' is applied. This approach, similar to the offset method used in CNC fine machining, is to make the offset area by expanding the contour with a designated width (Dong *et al.* 1993, Li *et al.* 1994, Hu *et al.* 1998). The advantage of the original contour offset approach is that the width of the offset area can be decided as desired.

In general, if there is narrow cross-section area of the part, the part is easily damaged in the narrow position during decubing process. The appropriate width of offset area is used for increasing the strength of narrow part, and it reduces the possibility to damage the part when the waste material is being removed. For the 'original contour offset approach', the width of offset area is determined by dividing the area of cross-section contour by the circumference length of the cross-section contour after sliced part. Equation (2) is used to determine the width of offset area. Figure 3b shows the original contour offset approach.

$$\text{Width of offset area} = \frac{\text{area of cross-section contour}}{\text{circumference of cross-section contour}}. \qquad (2)$$

3.2. *Fine crosshatch pattern in the inner region*

When generating machining plans, the basic task is to determine the optimal crosshatch pattern according to the shape of the cross-section contour. Although it is common to use a fixed crosshatch pattern throughout the LOM process, it is possible to use a different crosshatch patterns for different layers. When the cross-section of the part is less complex, a larger crosshatch is used, and when the cross-section is more complex a smaller crosshatch is used. The LOM process with a

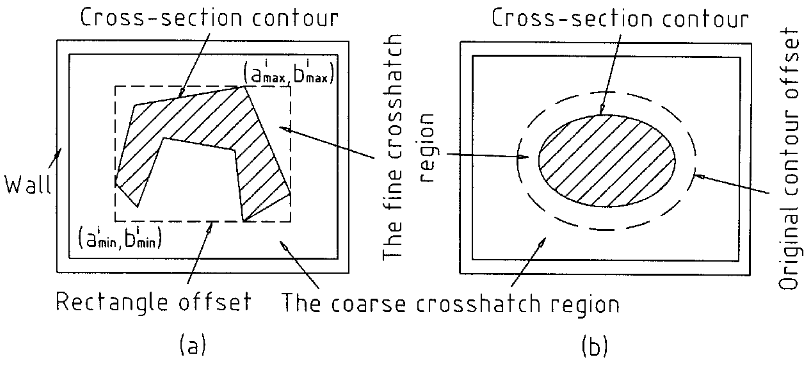


Figure 3. Two approaches for defining the offset section: (a) rectangle offset, (b) original contour offset.

smaller crosshatch requires a longer building time; however, it cuts waste material into smaller chunks and then saves the time consumed for the decubing process. On the other hand, the LOM process with a larger crosshatch requires a shorter building time but makes the decubing process more difficult and time consuming. The manufacturing time plus decubing time equals the total time consumed for the LOM process. Therefore, there exists an optimal crosshatch pattern in which both these two factors are taken into account.

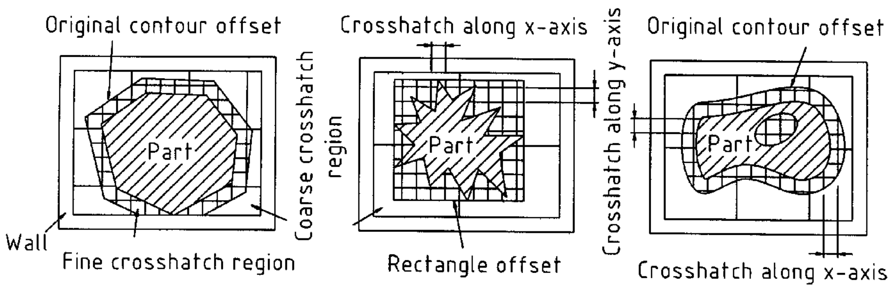
A few issues in selecting crosshatches are described below. There are four crosshatch patterns that are frequently used in the machining plan.

3.2.1. *Rule of selecting crosshatches for concave and convex shape*

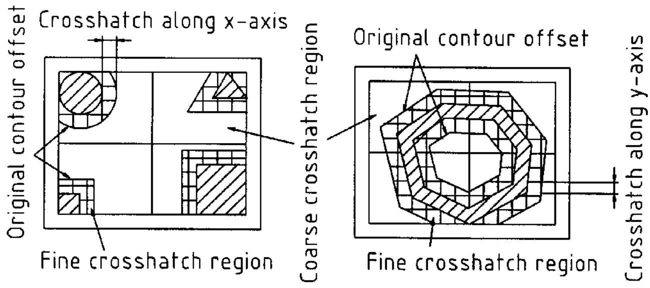
The laser path meets every vertex of the convex or concave shape is the ideal and compact crosshatch pattern. This is, however, difficult to implement. Therefore, crosshatches are usually less than the minimum edge of these features with convex or concave shape (figure 4a and b). To make the decubing process easier, it is usual to set the crosshatch size equal to half of the size of minimum edge.

For any arbitrary polygon with a convex shape, the interior angle of the neighbouring edges is $< 180^\circ$. For any arbitrary polygon with concave shape, the interior angle of the neighbouring edges is $> 180^\circ$. The crosshatch pattern can be determined using the following formula:

$$\text{Crosshatch size along } x\text{- or } y\text{-axis} < (\text{minimum length of polygon edge}/2). \quad (3)$$



(a) Convex part (b) Concave part (c) Pocket part



(d) Island part (e) Thin-wall part

Figure 4. Adaptive crosshatch pattern according to the shape of the cross-section contour.

3.2.2. *Rule of selecting crosshatches for pocket and island*

In general, it is essential to have at least two to four crosshatches surrounding each feature to ensure that crosshatches pass through any pockets or islands in the part along the x- and y-axes. For these features with groove, concave cavity, hole and so on, the pocket will be formed after slicing. Crosshatches should be less than half or one-quarter of the minimum length of a pocket. Similarly, for these features with cylinder, convex shape and so on, an island will be formed after slicing. Crosshatches are also less than one-half or -quarter of the minimum length of an island. In figure 4c and d, the minimum length of the pocket or island is always larger than the crosshatch size along the x- or y-axes to ensure that the crosshatch will come across any pocket or island in the part. Equation (4) is used to determine the optimal crosshatch size:

$$\text{Crosshatch size along } x\text{- or } y\text{-axis} < (\text{minimum length of pocket or island}/N), \quad (4)$$

where $N = 2\text{–}4$.

3.2.3. *Rule of selecting crosshatches for thin wall part*

The crosshatch size, in most cases, should be smaller or equal to the wall thickness of the part in order to make the strength of the waste material less than that of the wall part (figure 4e). This is because if the waste material is stronger than the thin wall of the part, it is easy to destroy the thin wall in the decubing process. Therefore, LOM is only suitable for building parts having a high ratio of volume:surface area, i.e. thick wall or large parts. To overcome the restriction, equation (5) determines the optimal crosshatch size:

$$\text{Crosshatch size along } x\text{- or } y\text{-axis} < \text{wall thickness of the part.} \quad (5)$$

3.2.4. *Rule of selecting crosshatches ensure that the larger crosshatches are an even multiple of the smaller crosshatches*

In general, when the size of the crosshatch is to be enlarged, it has to be multiplied by an even integer, and vice versa, when the size of crosshatch is to be downsized, it has to be divided by an even integer. Otherwise, the gridlines of the two crosshatch patterns will not match within a part block, and the staggered crosshatches will have a brick-layered effect, making them difficult to separate. The situation can be described by equation (6):

$$\begin{aligned}&\text{Larger cross-hatch size along } x\text{- or } y\text{-axis}\\&\qquad = 2N\times \text{ small crosshatch along } x\text{- or } y\text{-axis,}\end{aligned} \quad (6)$$

where $N > 0$ and $\in$ integer.

3.3. *Coarse crosshatch pattern in the outer region*

Usually, the size of crosshatches of the outer region is an integer multiple of that of the inner region (equation 7). As is known, the outer region is between the contour of the offset section and the wall, and the inner region is between the contour of part and contour of the offset section:

$$\begin{aligned}&\text{Coarse crosshatch size along } x\text{- or } y\text{-axis in the outer area}\\&\qquad = n \times \text{ fine crosshatch along } x\text{- or } y\text{-axis in the inner area,}\end{aligned} \quad (7)$$

where $N > 1$ and $\in$ integer.

3.4. *Projection method for overlap zone*

During the decubing process of proposed adaptive crosshatch approach, a so-called 'brick-layered effect' between layers will seriously increase the difficulty of decubing. The effect appears when the cross-section contour along z-axis is drastically changed and the same adaptive crosshatch pattern is used. The zone in which the brick-layer effect occurs is called the overlap zone shown in figure 5. It is opposite to an undercut. Undercut is a part protruded from the main body. However, the overlap zone is a retraction of the main body. Under such circumstance, the staggered crosshatch will make waste chunks difficult to be separated. To avoid this effect, a 'projection method' is applied (figure 6) described here.

Step 1. Divide the raw material along the z-axis at locations with a significant change in cross-sectional area. Therefore, the raw material will be divided into several portions.

Step 2. Label the portions from the bottom as A_1, A_2, $A_3, \ldots, A_n$.

Step 3. Take three successive portions from the A_i ($i = 1$) and calculate the vertical projection areas enclosed by the offset area, of each subdivision as A_1, A_{i+1}, A_{i+2}.

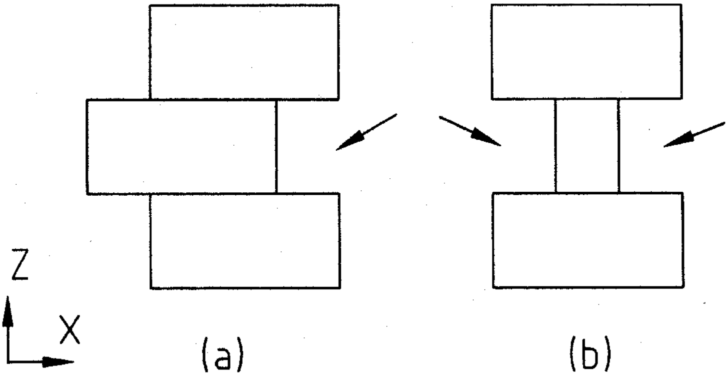


Figure 5. Examples of an overlap zone.

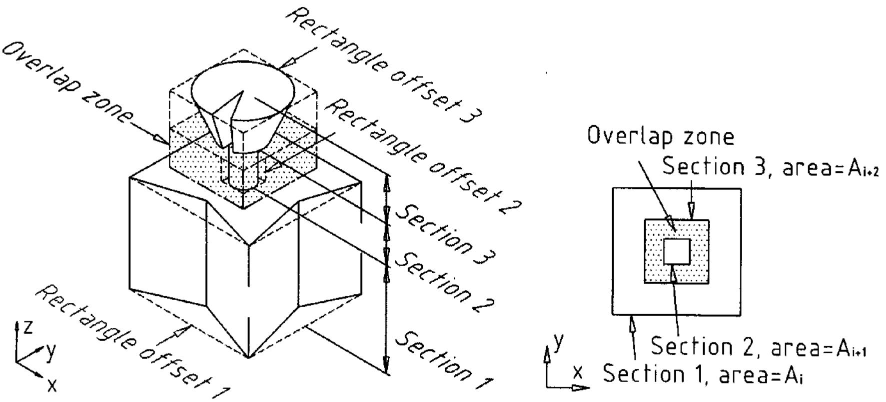


Figure 6. Projection method.

Step 4. Comparing areas of three consecutive portions. The overlap zone occurs when these three consecutive portions have a retraction along the z-axis. If there is no overlap zone, miss Step 5 and go directly to Step 6.
Step 5. Area of overlap zone is $A_i \cap A_{i+2} - A_{i+1}$.
Step 6. Go to Step 2 and set $i = 2$ and repeat the process until $i = N - 2$.

The laser path is traced along the contour of overlap zone, and the crosshatch pattern in the overlap zone is the same as that of the inner region between the contour of part and contour of the offset section.

4.1. *Procedures of adaptive crosshatch approach generation*

The flow chart of the adaptive crosshatch approach is shown in figure 7. The main procedures are stated as follows.

First, the .STL file is loaded and the preferred orientation is determined. The 'block' of the part is formed according to its minimum and maximum coordinate of x-, y- and z-axes. Second, make the offset area by expanding the contour with a designated width based on the shape of the cross-section contour. There are two offset approaches as stated in Section 3: the 'rectangle offset approach' is suitable for the part with concave-shape, while 'original contour offset approach' is suitable for the part with convex-shape, thin-wall, islands, pockets, etc. Third, the overlap zone is decided by the 'projection method' and the brick-layered effect is avoided to make the decubing process less difficult. The planning of the laser path in the overlap zone is traced along its contour and its crosshatch pattern is the same as that of the inner region. Fourth, the part is sliced into layers from the bottom up according to the sheet material thickness. Fifth, the fine crosshatch pattern is decided according to the

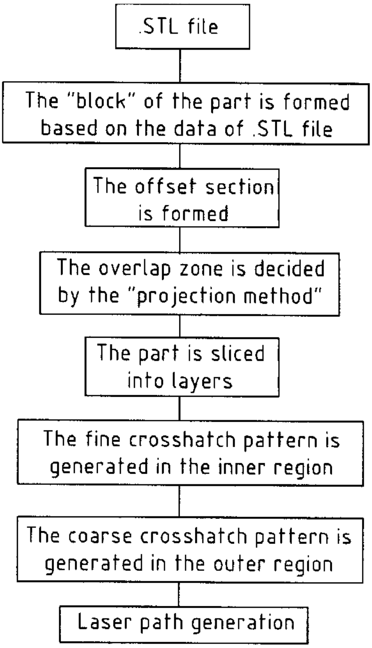


Figure 7. Procedures of an adaptive crosshatch approach generation.

shape of the cross-section contour of the sliced part enclosed by the inner region, which is between the contour of the part and contour of the offset section. Sixth, the size of the coarse crosshatch pattern in the outer region is an integer multiple of that of the inner region. The outer region is between the contour of the offset section and the wall. Finally, the laser path is generated by computation based on the different crosshatch pattern set.

4.2. *Verification*

The LOM1015Plus machine is used to verify the adaptive crosshatch approach. Its control software is LOMSlice^{TM} developed by Helisys Corporation. The material is LPH042 provided by the same company.

LOMSlice^{TM} software uses the default uniform crosshatch and it does not support the adaptive crosshatch setting. Therefore, the proposed crosshatch is simulated by manual manipulations of I-DEAS^{TM} CAD/CAM software. Three steps in figure 7, namely 'the offset section is formed', 'the overlap zone is decided by projection method' and 'the fine crosshatches pattern is generated in the inner region', are simulated by I-DEAS^{TM} CAD/CAM software. The procedures are stated as follows.

First, the .STL file is loaded and the designated width of offset area calculated by equation (2) is determined. Many blocks surrounded the 3D model are built in the offset area, their widths and lengths are determined according to the proposed rules of fine crosshatch pattern in the inner region mentioned in Section 3.2. Then, the blocks and the original 3D model are loaded to LOMSlice^{TM}. The fine crosshatch pattern will be generated after the blocks are sliced. The same method is used for crosshatch setting in the overlap zone. For the region outside the offset area, the appropriate crosshatch is set directly by LOMSlice^{TM} following the rule of coarse crosshatch pattern in the outer region mentioned in Section 3.3. The laser paths are generated according to the crosshatch setting, and they are just the same as the paths determined by LOMSlice^{TM}.

The above process will increase the effort involved, but it is also an effective way to evaluate the proposed adaptive crosshatch approach, since the crosshatch machining time and decubing time would be the same as the actual ones.

5. Example

To demonstrate the validity of the adaptive crosshatch approach, three different crosshatch methods—uniform crosshatch, adaptive crosshatch-original contour offset approach (OCOA) and adaptive crosshatch-rectangle offset approach (ROA)—are compared (figure 8). The test sample is an .STL file of a 'wine glass' whose volume ratio of waste material to part is 636%, much bigger than 100% of the criteria rule of equation (1). The comparison resulted from the experiment is shown in table 2. Five criteria have been used for comparison. The first three items in table 2, 'total length of laser path', 'decubing time' and 'possibility to damage the part', are obtained from experiment, and the other two items, 'machining time' and 'laser power consumption', are derived from their proportional relations with 'total length of laser path'.

As shown in table 2, the total length of the laser path with 'OCOA' has a relative minimum value (1925 m) compared with 'uniform crosshatch' (3636 m) and 'ROA' (2416 m). Therefore, OCOA is stated as 'better' and ROA is 'good' in the items of machining time and laser power consumption.

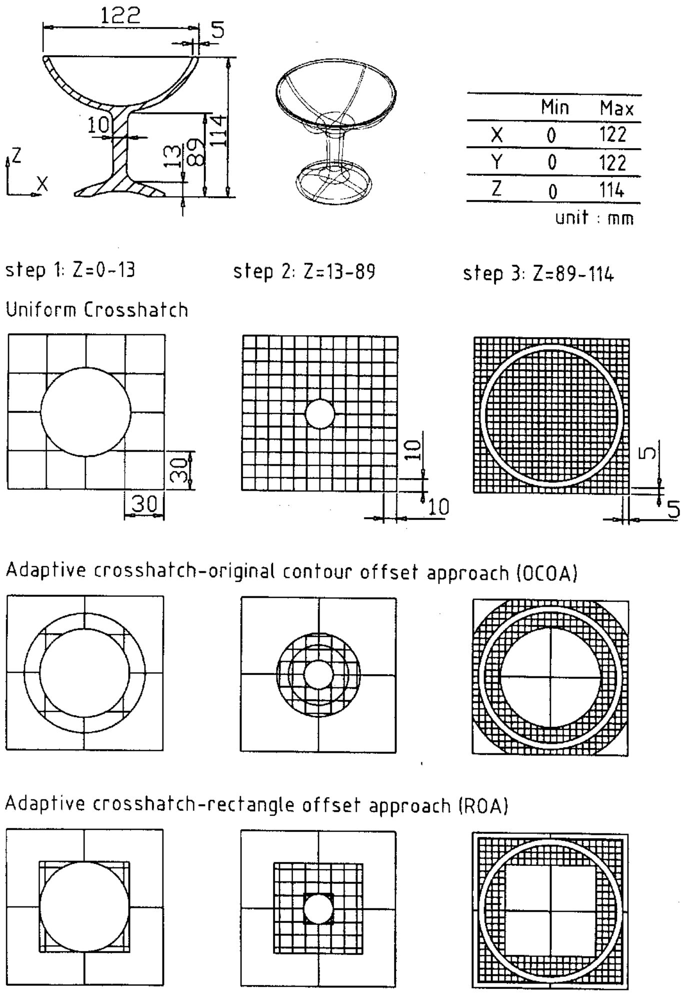


Figure 8. Example of an adaptive crosshatch approach.

	Total length of laser path (m)	Decubing time (m)	Possibility to damage the part	Machining time	Laser power consumption
Uniform crosshatch	3636 m	63	worst	worst	worst
Adaptive crosshatch original contour offset approach (OCOA)	1925 m	39	good	better	better
Adaptive crosshatch rectangle offset approach (ROA)	2416 m	33	better	good	good

Table 2. Comparison of the uniform crosshatch and adaptive crosshatch approaches.

Decubing time is apparently reduced with OCOA (39 min) and ROA (33 min) because the coarse crosshatch chunks in the outer region are easier to remove. ROA has the minimum decubing time due to its obvious rectangle shape. For the similar reason, the possibility to damage the part with the ROA is also reduced because the boundary of the rectangle shape is comparatively easier to be distinguished and that reduces mistakes in the decubing process.

In summary, the adaptive crosshatch approach apparently surpasses the uniform crosshatch in following items: decubing time, machining time, laser power conservation and possibility to damage the part.

6. Conclusions

The main contributions of the paper are the development of methods for increasing the machining efficiency without changing the hardware configuration of the LOM machine. The central idea in the proposed approach is to change the whole strategy in setting the crosshatch. However, since the rule of selecting the optimal crosshatch sizes is pretty much intuitive, the best way to put our idea into practice is to build up a database or a table of parameters through experiments. The users of LOM machines could, therefore, have a clear reference in determining the crosshatch sizes when they are planning their machining works.

References

Cohen, A. L., 1991, Technology focus: laminated object manufacturing. *Rapid Prototyping Report*, **1**, 6–8.

Dong, Z., Li, H. and Vickers, G. W., 1993, Optimal rough machining of sculptured parts on a CNC milling machine. *Journal of Engineering for Industry*, *ASME,* **115**, 424–430.

Feygin, M., 1994, Apparatus and method for forming an integral object from laminations. US Patent No. 5,354,414.

Feygin, M. and Pak, S. S., 1997, Apparatus for forming an integral object from laminations. US Patent No. 5,637,175.

Feygin, M. and Pak, S. S., 1999, Laminated object manufacturing apparatus and method. US Patent No. 5,876,550.

Hu, Y. N., Tse, W. C., Chen, Y. H. and Zhou, Z. D., 1998, Tool-path planning for rough machining of a cavity by layer-shape analysis. *International Journal of Advanced Manufacturing Technology*, **14**, 321–329.

Klosterman, D., Chartoff, R., Osborne, N. and Graves, G., 1997a, Automated fabrication of monolithic and ceramic matrix composites via laminated object manufacturing (LOM). *Solid Freeform Fabrication Symposium Proceedings*, University of Texas at Austin, pp. 537–549.

Klosterman, D., Priore, B. and Chartoff, R., 1997b, Laminated object manufacturing of polymer matrix composites. *Proceedings of the 7th International Conference on Rapid Prototyping*, University of Dayton, San Francisco, CA, pp. 283–292.

Li, H., Dong, Z. and Vickers, G. W., 1994, Optimal tool-path pattern identification for single island, sculptured part rough machining using fuzzy pattern analysis. *Computer-Aided Design*, **16**, 787–795.

Pak, S. S. and Nisnevich, G., 1994, Interlaminate strength and processing efficiency improvements in laminated object manufacturing. *Proceedings of the 5th International Conference on Rapid Prototyping*, University of Dayton, OH, pp. 171–180.

Sonmez, F. O. and Halh, H. T., 1998, Thermomechanical analysis of the laminated object manufacturing (LOM) process. *Rapid Prototyping Journal*, **4**, 26–36.

Thomas, C. L., 1996, Automating sheet-based fabrication: the Conveyed-Adherent^{TM} process. *Solid Freeform Fabrication Symposium Proceedings*, University of Texas at Austin, pp. 281–290.