Accuracy Study on Laminated Object Manufacturing for the Metallic Functional Parts with Complex Surface

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ABSTRACT

The feasibility of using the Laminated Object Manufacturing (LOM) process for rapid manufacturing of the metallic functional parts with complex surface was studied in this paper. The theoretical manufacturing error and the quantity of remaining material to be removed by finish manufacturing process caused from current LOM process were analyzed, and compared with 3-D numerical control manufacturing. A new approach for cutting metallic laminating layer was presented for reducing theoretical manufacturing error and quantity of remaining materials. Case study of cylinder surface demonstrates the effects of new LOM process that it could increase the thickness of the laminating layer from 0.05-0.1mm to 1.0mm grade. Even with such thicker metallic laminating layer, we also can get similar to or lower theoretical manufacturing error and remaining material quantity than current LOM process. It may indicate that metallic functional parts with complex surface could be rapidly manufactured with new LOM process.

INTRODUCTION

In past decade, a lot of important breakthroughs have been made in the theoretical research and its application about the rapid prototyping and manufacturing (RP/M) technology [1]. Although there are some reports in which the ceramic is used as the modeling materials [2], in the most case the modeling materials used are those such as plastics, paper or wood. During its initial development stage, RP/M technique is usually used to evaluate the correctness of the three dimensional model resulted from CAD, the materials such as plastics used as modeling materials are good enough for that purpose. With its application extending to the fields such as the check of design, the evaluation of performance, the trial fabrication or the manufacturing of the functional parts, RP/M technique must be further improved with the effort to use some other materials rather than the ones mentioned above. One of the attempts is to use metal as the modeling materials [3].

There are some reports using the sheet metal as modeling materials by laminated object manufacturing (LOM) for manufacturing the metallic functional parts [4]. After examining on the available results, we have realized that there are some problems to be solved when using the sheet metal as the modeling materials in LOM process, one of them is how to get the expected laminating accuracy. It is well known that the thinner the laminating layer is, the higher the modeling accuracy is. The thickness of laminating layer for the available LOM processes, which use paper, plastics or wood plate as modeling materials, is usually only 0.05-0.1mm. For using metal plate as modeling material, there is a research report of using sheet steel of 0.2mm thick, and the attempt would be made to use thinner sheet metal plates. But using thinner sheet metal brings about other problems, for example, the strength of steel decreases with the increase of the modeling time. In addition, the sheet steel thinner than 0.2 mm with the bond coated on its both surface is difficult to be made practically.

In this paper the accuracy study on LOM is presented. Authors have done a basic analysis on theoretical manufacturing error for LOM in reference [5]. Based on the further analysis of the theoretical manufacturing error and the quantity of remaining material to be removed by finish process (that is said as remaining quantity) caused by LOM process and 3-D numerical control manufacturing (that is said as 3-D NC process), a new LOM process to reduce the theoretical manufacturing error and remaining quantity is proposed.

THE ANLYSIS OF THEORETICAL ERROR AND REMAINING QUANTITY

Here we use a quarter cylinder surface as the object of research. With this object, the theoretical manufacturing error and remaining quantity for both of the current LOM process and 3-D NC process are explored.

Current LOM Process

Laminating principle of the LOM method for the quarter cylinder surface is shown by fig.1, from the figure we know that there exist stair steps between each laminating layer and the modeling surface. To get the correct surface these stair steps have to be removed by the

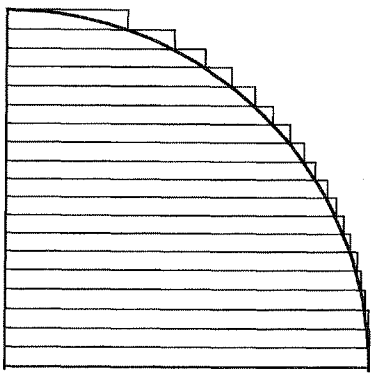

Fig.1 Laminating principle of LOM

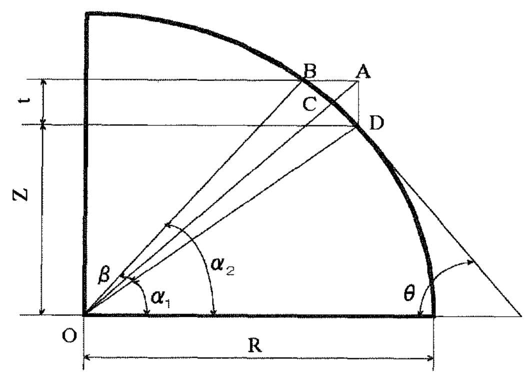

Fig.2 Theoretical error and remaining quantity of LOM

successive finish process, here the stair steps are called remaining quantity. The largest distance between each laminating layer and the modeling surface is defined as the theoretical manufacturing error of this layer. In fig.2 one laminating layer taken from the quarter cylinder surface is shown. In more detail, where the height of the layer is z, the thickness of the layer is t, the area of the curved triangle *ABD* is the remaining area to be removed, which is represented by S_1. The volume formed by the area of S_1 stretching W (the width of the cylinder surface) along the axle of cylinder is the remaining quantity, which is represented by V_1. The height *AC* of the curved triangle *ABD* along the direction of radius is the theoretical manufacturing error, which is represented by Δ_1. Then we have the following equation:

$$\Delta_1 = \sqrt{t^2 + R^2 + 2zt} - R \tag{1}$$

$$S_1 = \frac{1}{2}[Rt(\cos\alpha_1 - \cos\alpha_2) - R^2(\beta - \sin\beta)] \tag{2}$$

$$V_1 = S_1 W \tag{3}$$

Where

$$\alpha_1 = \sin^{-1}(z/R)$$

$$\alpha_2 = \sin^{-1}[(z+t)/R]$$

$\beta = \alpha_2 - \alpha_1$

α_1, α_2, β and all the quantities of angles are measured in radian measurement.

3-D NC Process

Suppose the process of the 3-D numerical control manufacturing is the same as that of LOM, i.e. the process goes along the cylinder surface of the radius of R, the radius of ball end mill is r (as shown in fig. 3). The center of the ball end mill is O_1 on the height of z, and after one circle it changes to O_2. The feed quantity between the two cutting along the direction z is f. From the figure we know that the area between the two cuttings and modeling surface (the area of the curved triangle ABD) is the remaining area to be removed, which is represented by S_2. The volume formed by the area of S_2 stretching W along the axle of the cylinder is the quantity of remaining materials, which is represented by V_2. The height *AC* of the curved triangle ABD along the direction of radius is the theoretical manufacturing error, which is represented by Δ_2. By analysis we have the following results:

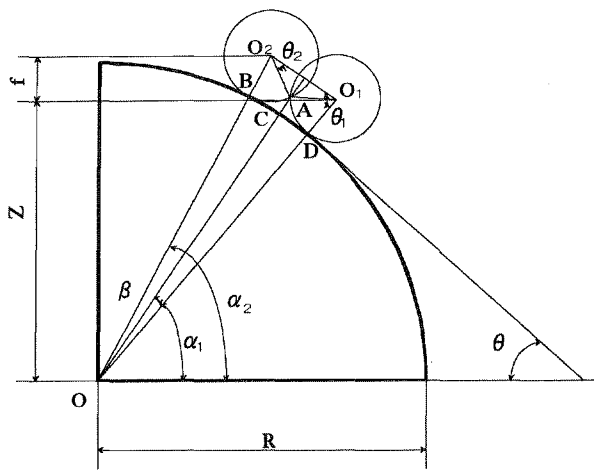

Fig.3 Theoretical error and remaining quantity of materials of 3-D NC process

$$\Delta_2 = (R + r)\cos\beta - R - \sqrt{r^2 - [(R + r)\sin\beta]^2} \quad (4)$$

$$S_2 = (R + r)^2 \cos\beta \sin\beta - R^2\beta - r(R + r)\sin\beta \sin\theta_2 - r^2(\theta_1 - \theta_2) \quad (5)$$

$$V_2 = S_2 W \quad (6)$$

Where

$\alpha_1 = \sin^{-1}[z/(R + r)]$

$\alpha_2 = \sin^{-1}[(z + f)/(R + r)]$

$\beta = \frac{1}{2}(\alpha_2 - \alpha_1)$

$\theta_1 = \frac{\pi}{2} - \beta$

$\theta_2 = \cos^{-1}[(R + r)\sin\beta / r]$

Analysis for the Theoretical Manufacturing Error and Remaining Quantity

Let R=100mm, W=50mm, t=1mm, r=5mm, and f=1mm, where R is the curvature's radius of the three-dimensional surface, and W is its width, t is the thickness of laminating layer, r is the radius of ball end mill, f is the feed quantity of finish milling.

By equations of (1) and (4), the theoretical manufacturing error curves of both the LOM process and 3-D NC process can be computed, which are shown by fig.4, where Δ_1 and Δ_2 are the theoretical manufacturing error curves of LOM and 3-D NC process correspondingly. With the increase of the z coordinate's value of laminating layer, the included angle of θ between the tangent plane of the three dimensional surface and the laminating layer changes from $\pi/2$ (90°) to 0, as a result the theoretical errors of both processes increase and reach their maximums where θ approaches to 0. The maximums of the theoretical error are Δ_{1max}=0.99mm (almost the same as the thickness of the laminating layer), and Δ_{2max}=0.24mm (1/4 of the feed quantity). In addition, if we have a look at the distribution property of the error, we know that the theoretical error from current LOM process is far larger than the one from 3-D NC process.

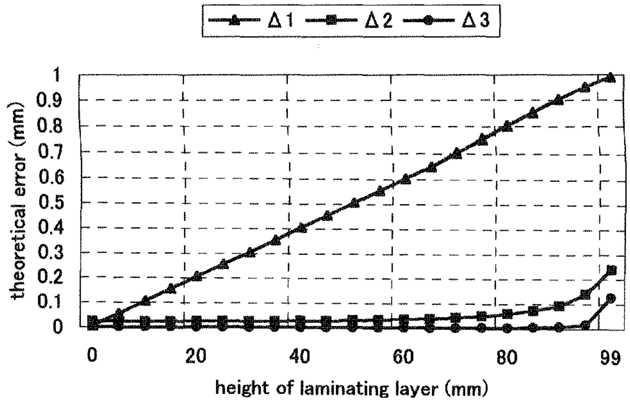

Fig.4 The theoretical manufacturing error curves

By equation (3) and (6) the quantity of remaining material for each laminating layer or between twice cutting can be computed, the sum of the quantity of remaining materials for the all laminating layer on the quarter cylinder or among all cutting paths are ΣV_1=2353.0mm^3, ΣV_2=124.8mm^3, which are shown in fig.5. Both the remaining materials of the LOM and 3-D NC processes increase with the decrease of the included angle θ between the tangent vector of modeling surface and the laminating layer, and reach their maximum where θ approaches to 0, i.e. the maximum values are V_{1max}=234.6mm^3, V_{2max}=11.8mm^3. The results show that the maximum quantity of the remaining materials of the current LOM process is 18.9 times greater, and the sum of the quantity of remaining materials is 17.9 times greater than that of the 3-D NC process.

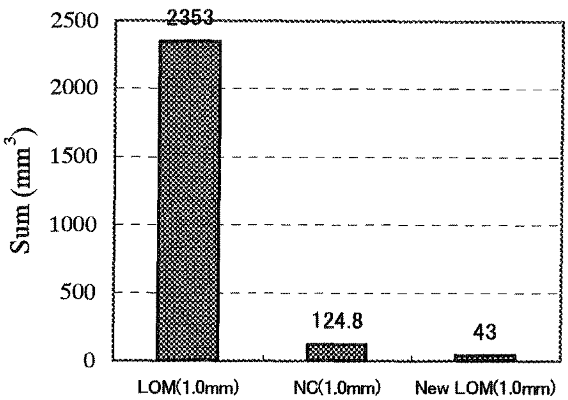

Fig.5 The sum of remaining materials quantity

Based on the analysis above, it is proved that although the current LOM process has high efficiency than 3-D NC process and it also simplifies the complexity of the 3-D surface to be manufactured, but it has the disadvantage of poor manufacturing accuracy, which means there is more quantity of remaining materials left, so it needs much time for further finish process. To improve the accuracy of the current LOM process, there are two choices, one is to decrease the thickness of the laminating layer, which is 0.05-0.1mm in available LOM processes, and the other is to search for more efficient LOM process. In this paper we explore some more efficient LOM process to improve the manufacturing accuracy of current LOM process.

NEW METHOD OF LOM PROCESS

The New Approach for Improving the Manufacturing Accuracy

From the analysis above we know that in order to reduce the theoretical error and the quantity of remaining materials, we have to reduce or eliminate the left steps between each laminating layer and modeling surface, which are the main source of the error. Let us have a look at the manufacturing process of each laminating layer. From the bottom to top along the direction of z coordinate, the laser or ball end mill cuts the perimeter of the cross sectional area of the 3-D surface in LOM at present. When θ is small, the left stair steps are large, and as a result the manufacturing error and the quantity of the remaining materials are also large. Here we suppose that in new LOM process the laminating layer is cut by laser or ball end mill along the tangent vector *CD* of modeling surface passing the mid point *E* of the laminating layer for the convex surface, or along the direction *C'B'* of intersection points between modeling surface and up and down sides of laminating layer for concave surface, shown as fig. 6. By the figure it is obvious that the area of remaining materials of the new LOM process is much smaller than that of current LOM process (the curved triangle *ABF* for convex surface or *A'B'C'* for concave surface).

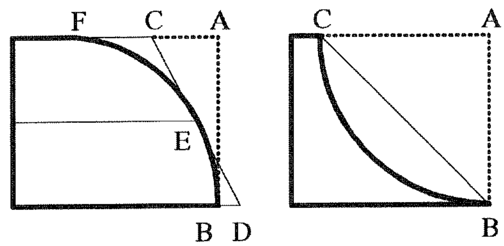

Fig. 6 The principle of new LOM process

The Analysis for the New LOM Process

Here we use the same convex quarter cylinder surface as the example of computation, as shown in fig. 7. Where *A* is the intersection point between the center point plate of laminating layer and modeling surface. The points *B* and *C* are the intersection points between up and down sides of the laminating layer and the tangent line of modeling surface passing the point A. From the figure, we know that the sum of the area of curved triangle *ABE* and *ACG* is the remaining area for the new LOM process, which is represented by S_3. The larger one of the height along the radius direction, i.e. Δ_{31} and Δ_{32}, is the theoretical error of the laminating layer, which is represented by Δ_3. The remaining area and quantity to be removed can be computed by equation (7)-(11):

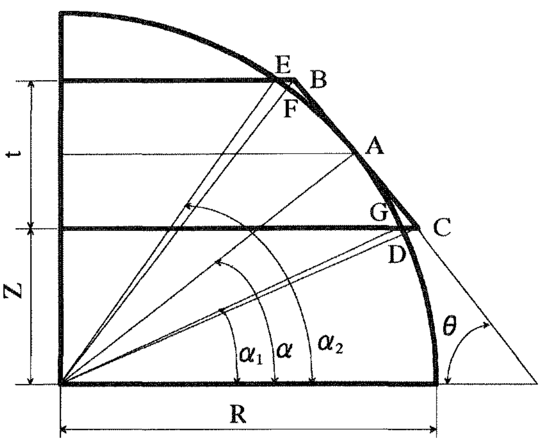

Fig. 7 Theoretical error and quantity of remaining materials of new LOM process

$$\Delta_{31} = \sqrt{(R\cos\alpha - \frac{t}{2}\tan\alpha)^2 + (z+t)^2} - R \tag{7}$$

$$\Delta_{32} = \sqrt{(R\cos\alpha + \frac{t}{2}\tan\alpha)^2 + z^2} - R \tag{8}$$

$$\Delta_3 = \max[\Delta_{31}, \Delta_{32}] \tag{9}$$

$$S_3 = \frac{tR}{4}(2\cos\alpha - \cos\alpha_2 - \cos\alpha_1) - \frac{R^2}{2}[\alpha_2 - \alpha_1 - \sin(\alpha_2 - \alpha) - \sin(\alpha - \alpha_1)] \quad (10)$$

$$V_3 = S_3 W \quad (11)$$

Where

$$\alpha_1 = \sin^{-1}(z/R)$$

$$\alpha_2 = \sin^{-1}[(z+t)/R]$$

$$\alpha = \sin^{-1}(\frac{z+t/2}{R})$$

Comparison Analysis

The same as above, let R=100mm, W=50mm, t=1mm, the theoretical error and quantity of remaining materials are computed here.

According to equation (7)-(9), the theoretical manufacturing error is computed, and its curve is shown as Δ_3 in fig. 4, which is far lower than that of current LOM process and the 3-D NC process. Its maximum is Δ_{3max}=0.125mm, which is only 12.6% of that of current LOM process, and 52.1% of that of 3-D NC process.

The quantity of remaining materials of new LOM process can be computed by equation (11), and its maximum value is V_{3max}=28.7 mm^3, which is 7.1 times smaller than the same quantity of current LOM process, and 1.4 times larger than the same quantity of 3-D NC process. But the sum of the quantity of remaining materials is ΣV_3=43.0mm^3, shown in fig.5, which is 53.7 times smaller than the same quantity of current LOM process (ΣV_1=2353.0mm^3), and 1.9 times smaller than the same quantity of 3-D NC process (ΣV_2=124.8mm^3).

In the following we further compare the new LOM process with the available practical LOM process. The thickness of laminating layer is from 0.05 to 0.1mm in available practical LOM process and 0.2mm in reference [4], so we compute the theoretical error and the quantity of remaining materials for available practical LOM process when the thickness

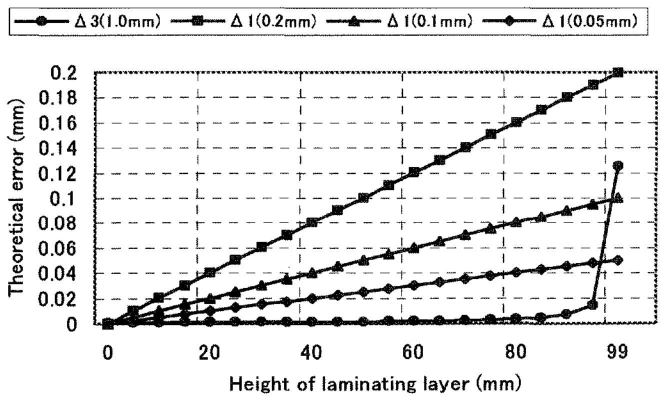

Fig.8 The comparison curve of theoretical error

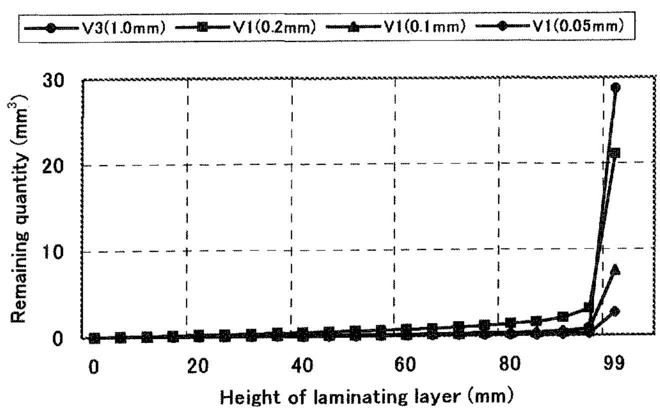

Fig. 9 The comparison of remaining material quantity

of laminating layer are t=0.05, 0.1, and 0.2mm, and compare the results with those obtained by new LOM process.

In fig. 8 the theoretical errors are compared. Although when t=0.05 and 0.1mm, the maximum theoretical error of current LOM process are smaller than the same quantity of the new LOM process in which the thickness of laminating layer is t=1mm, but in overall distribution, the new LOM has the most small theoretical error.

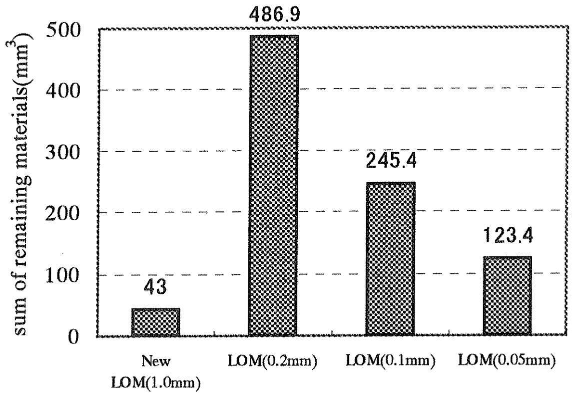

Fig.10 the comparison of remaining materials

In fig.9 the quantities of remaining materials for the single laminating layer are compared. Although the new LOM has the largest maximum remaining quantity for the single laminating layer, because it has the much larger thickness than current LOM process, but the sums of the remaining quantity for three different thickness of laminating layer in current LOM process are larger than that of the new LOM process, i.e., $\Sigma V_1(0.2)=3139.5mm^3$, $\Sigma V_1(0.1)=1570.3mm^3$, $\Sigma V_1(0.05)=785.3mm^3$, which are 33 times, 16.7 times and 8.5 times larger than that of the new LOM process ($\Sigma V_3(1.0)=95.1mm^3$) respectively, shown in fig.10.

EXAMPLE PARTS

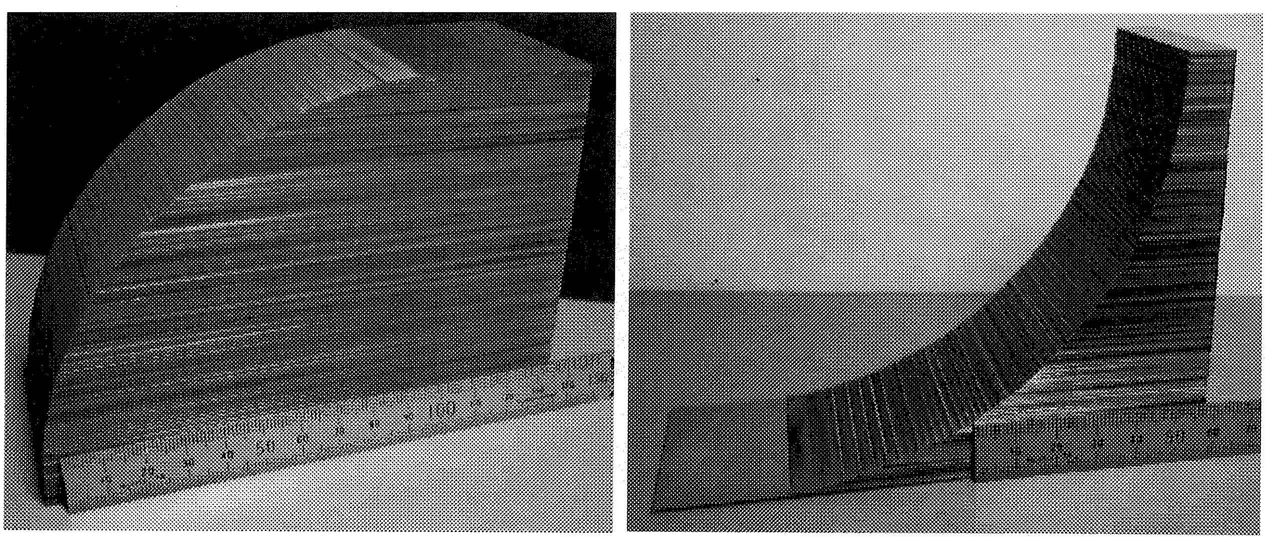

Fig.11 the photo picture of example parts

The example parts of quarter cylinder surface were made by new LOM process. In this case, sheet steel of 1.0mm thickness was used as modeling materials, the radius of cylinder surface is 100mm, and its width is 50mm, just like the analysis above. The wire electrical discharge machine was used to cut the laminating layers along the tangent vector of modeling surface. We have gotten two example parts, one was a convex cylinder surface part, and the other was a concave cylinder part shown as fig. 10. From this photo picture we can see that stair step effect was obviously restrained and smooth modeling surface have been obtained.

CONCLUSION

Based on the analysis above, the following conclusions can be drawn:

1. In the current LOM process, the stair steps are used to make close to the modeling surface, which result in larger theoretical manufacturing error and remaining materials quantity to be removed. To get higher manufacturing accuracy and reduce the remaining materials quantity fairly thin laminating layer (about 0.05-0.1mm) must be used.

2. When sheet metal is used to manufacture the functional parts by the LOM process, available thickness of laminating layer being 0.05-0.1mm could not be used for the limitation on the modeling strength and building time of model.

3. By the new LOM process proposed in this paper, the thickness of laminating layer of the modeling materials can reach 1.0mm grade. In addition the resulting accuracy and remaining quantity are near or superior to those obtained by the current practical LOM process with the thickness of laminating layer being 0.05-0.1mm. This means the new LOM process can be treated as a rapid manufacturing method for metallic functional parts.

4. To use the new LOM process to manufacture metallic functional parts with metal sheet as modeling materials, some topics such as NC programming of four-dimension, the process of laser cutting, the bond technology for laminating layer, must be studied further.

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