The Approach of Complex Insert Packaging Fabrication in Stereolithography

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Abstract

The approach of complex insert packaging fabrication in stereolithography is studied in the paper. There are many difficulties being overcome, such as the dispensing shadowing problem caused by the geometric shape of insert, the polymer feeding problem caused by greater insert height than the layer thickness, and the positioning problem of insert that leads to instability of packaging. These drawbacks led to unsatisfactory results of the insert packaging in stereolithography. In order to solve the problems, a new method of complex inserts packaging fabrication in stereolithography is proposed in this paper. Based on the geometric information, function and assembly direction of the inserts, the packaging approach is developed. The approach proposed in this paper has been verified by experiments. It brings considerable contributions to the application of insert packaging in stereolithography. It is also favorable to the improvement of insert packaging efficiency and assembly fabrication.

Keywords: Rapid Prototyping, Solid Freeform Fabrication, Insert Packaging, Insert

1. Objectives and Motives:

Solid freeform fabrication (SFF) or rapid prototyping (RP) has displayed amazing potentials in the realms of product design and rapid manufacturing. From the literatures of the recent years, it is known that the future research trend of RP is small-sizing of rapid prototyping objects [1] and the manufacturing of assembling objects having complex functions. This paper aims at solving the problems and proposing a new processing method of insert packaging encountered in SLA's manufacturing of complex shape, functional mechanical structure and assembling objects.

In the early stage of RP development, it tends to be applied in the construction of original mold in the area of industrial design. However, in recent years, it tends to develop towards the manufacturing of functional assembling objects. Under an acceptable tolerance, the manufactured parts carry good precision, excellent surface precision and high flexibility. This enables a total process of manufacturing the finished product, without going through additional assembly [2] [3]. Furthermore, it can also establish the procedure that the parts of different materials are all embedded in the simple-structured RP object [4], such as embedding the parts of sensor, controller and bearing etc. into RP before the manufacturing of RP or during its fabrication.

Kataria [5] et al. explored the method of using photo polymer (SLA) to construct complex mechanism. Focusing on the various processing features of SLA, such as the design of fixture, the interference problems of recoating and insert, geometric shape of insert, positioning and fixture mechanism, and geometry tolerance etc., they proposed a series of process planning methods, and developed a multiple-shaft SLA machine [6], exploring into the RP processing realm in times of manufacturing the complex assembling object. However, the problems of dispensing shadowing, recoater interference, positioning and fixture etc. still limited the workability for SLA to manufacture assembling object and complex inserts.

In order to avoid obstructing or damaging the functions of flexible part, Chad A. Moore et al. [7] studied the method to embed flexible part into multi-material prototype, maintaining the shape of the flexible part in the process, and accurately controlling the geometric shapes in the contacting area of different materials. Finally, they proposed a series of processes.

According to the theory that SLA process has to undergo post-cure processing treatment after the product is completed, this paper proposes “online insert embedding process.” By using the pre-analyzed and pre–designed component, support and cavity, the insert is positioned, and then photo polymer is poured in. Afterwards, post curing processing treatment is made to solidify the required part in order to meet the objective of embedding in specific work-piece.

2. Approach

The online insert embedding process proposed by this paper is to solve the problems currently encountered by SLA when manufacturing the assembling object, complex geometric structure and functional structure. Therefore, algorithm of support of structure with geometric features is proposed, and furthermore, “online insert embedding process” is developed. It is hoped that the limitation of embedding insert in geometric shape in the SLA process can be eliminated. Focusing on the procedures of online insert embedding process and the theory of algorithm of support of geometric feature structure, detailed introduction and investigation are elaborated herein.

Figure 1 shows the flowchart of SLA process. Among the various RP machines, SLA process is the one with the highest precision. However, due to the problems of laser system, recoating system and the need to construct supporting material, lots of obstruction have been encountered during online embedding of work-piece.

The procedures of online insert embedding process proposed by this paper are as follows:

First of all, determine the manufacturing direction of object. Judge whether the mobility of insert has to be maintained. These are the key references for selecting suitable manufacturing principles. If the insert has to be fixed in the RP object, analyze whether the feature structure of its shape and the geometric shape would impose any difficulties in times of embedding, so as to determine whether the support of featured structure should be established or not. The following two points are the factors when considering the positioning of insert:

i. If support of featured structure is not required, a cavity that meets its geometric shape should be designed.

ii. If support of featured structure is required, the ***algorithm of support of geometric feature structure*** should be used to design its featured support structure, so as to place and position the insert and avoid the difficulties and size difference when designing the cavity of RP object for the embedding of complex insert.

If the insert needs to keep its mobility, we should analyze the feature structure of the external appearance of the insert, so as to judge whether the embedding direction of the insert might cause any interferences. The following two points are the factors for considering the mobility of insert:

i. If interference occurs, consider changing the forming direction of prototype.

ii. If interference does not occur, cover the insert with a thin layer of wax as a pre-treatment of the surface of the insert.

Upon completion of the above procedures, RP semi-product can be manufactured immediately, and then the insert can be embedded. After that, suitable volume of photo polymer should be poured in, and the procedure of vacuum extraction is undertaken. Then the product is put into the ultra-violet oven for solidification treatment, acquiring the final product. Finally, the wax layer between the mobile object and the RP object should be removed after solidification treatment. The procedures of online insert embedding process described herein are shown in Figure 2.

2.1 Processes of Online Insert Embedding Approach

Focusing on the functional and characteristic differences of insert, the above procedures can be summarized into three different treatment methods. Detailed description of these three processes is as follows:

Process 1：

The embedding of a circular shaft with different sectional area, as shown in Figure 3, is taken as an example. In general SLA process, as such work-piece is embedded, the insert has to be divided into two parts to avoid the problem of recoating interference. The "online insert embedding process" proposed in this paper adopts the pre-designed depression that meets the feature structure of the insert, which then embeds the insert according to the required direction.

After embedding, appropriate volume of photo polymer is poured in up to the surface height. Finally, post-cure processing treatment is undertaken to acquire the final product. This process carries two merits: first of all, the avoidance of the problem of recoating interference, and secondly, additional dismantling of circular shaft is not required.

Process 2：

If the shape of the insert is too complex to design the cavity contour of RP object, which ultimately causes the failure of embedding the insert, then ***the algorithm of support of geometric feature structure*** proposed herein should be employed.

While determining the manufacturing direction of RP object, researcher has to consider whether the shape structure of the insert might cause any problem to the embedding, and undergo an analysis of feature structure. The process is as follows: After horizontal scanning of the shape of the insert, the related information to its shape can be obtained. Then select the feature support curve to establish the RP feature support.

Next, use normal vector method to judge whether interference will be caused between the established RP feature support of this model and the insert. If there is no such phenomenon, select an appropriate thickness for the growth of solid along the curve, and build a support structure below the solid. If there is interference between the feature support and the insert, the growth of solid is not required.

Upon completion of the above procedures, input the file into RP system for manufacturing of RP semi-product, and then embed the insert. After completion of embedding, pour in appropriate volume of photo polymer. As the procedure of post-cure processing is undertaken, put the product in ultra-violet oven for solidification treatment so as to obtain the final product.

According to the above processes, we can further indicate the various procedures by a schematic diagram in Figure 4.

Process 3：

If the mobility of the insert has to be maintained, whether the embedding direction of the insert is workable should be evaluated first. Then analyze the feature structure of the shape of the insert so as to judge whether any interferences will occur between the feature structure of the insert and the RP object. If there is no such interference, proceed with surface treatment of the insert by pasting a thin layer of wax.

Upon completion of the above procedures, a suitable cavity for embedding of the insert should be designed on the RP object. Next, manufacture the RP semi-product, embed the insert, and then seal the gap between the insert and the RP object by wax in order to avoid the leakage of photo polymer. After the treatment, pour in appropriate volume of photo polymer. Having gone through procedure of vacuum extraction, the product is put in the ultra-violet oven for solidification treatment. Then the wax layer is removed to acquire the final product. The process is shown in Figure 5.

2.2 Rules of Lateral Support of Insert

In order to support and position the insert effectively, a lateral support of feature algorithm of insert should be developed to collaborate with the online insert embedding process. Through the analysis and determination by this algorithm, an RP support can be established along the 3D external contour of the insert. This section describes and investigates into this algorithm.

In describing the algorithm, this paper takes the use of SLA for online insert embedding as an example. First of all, a cavity of RP object is designed on the CAD. Next, the RP object is manufactured, and finally the insert is embedded into the cavity of the RP object. In this process, there should be a tolerance between the RP object and the insert. And this cavity is designed according to the deviation of the external structure of the insert to a fixed size tolerance. Since the insert is embedded in the process, the cavity is full of photo polymer. Thus, when the insert is embedded, the residue of photo polymer solvent, which is left in the gap between the cavity and the insert in times of insert embedding, makes it difficult for the insert and the RP object to collaborate with each other, and causing loose in embedding subsequently.

As shown in Figure 5, there must be a certain tolerance between the insert and the cavity. The design of a lateral positioning structure at the RP object can improve the matching problem between the insert and the RP object. By so doing, the RP object can contact the insert. Besides, position the insert more effectively, a small gap should be left before the processing for easier control of the pouring of photo polymer.

In order to embed and position the insert rapidly and effectively, the lateral support of feature algorithm of the insert is proposed. This paper divides it into boundary projection contour, contour curvature definition and establishment of lateral support point, which then further discuss into these three steps.

Step 1: Boundary Projection Contour

To avoid the creation of interference between the insert and the RP object in the embedding process of the insert, the maximum projection area of the insert in the embedding direction should be acquired. Suppose that when a parallel light irradiates downward from the top end of the insert, there is a shadow of the insert appeared at the bottom. This shadow is just the maximum projection contour in such embedding direction. Taking a shaft with changeable sectional area as an example, the maximum projection contour, as shown in Figure 6, can be acquired after projection.

The maximum boundary projection contour is calculated by using equations (1) – (2).

Suppose that the contour of the projection contour is an enclosed curve composed of n segments of straight line. Then it can be equally divided into m points in anti-clockwise direction. The contour boundary S can be defined as:

$$S = \{ P_j = (x_j , y_j) \mid j = 1,2,3.........m \} \quad (1)$$

In the above equation, P denotes the coordinates of the contour boundary, and m denotes the number of equation. When S is divided into n subsets, S can be indicated in equation (2) below:

$$S_i = \{ P_{ij} = (x_{ij} , y_{ij}) \mid j = 1,2,3........m, \quad i = 1,2,3...........n \} \quad (2)$$

And S can be expressed as:

$$S = S_1 \cup S_2 \cup S_3........... \cup S_n = \cup S_i$$

Where, $S_i = \{ P_{ij} = (x_{ij} , y_{ij}) \mid j = 1,2,3........m, \quad i = 1,2,3...........n \}$

Step 2: Contour Curvature Definition

The determinant of contour curvature can be calculated according to the definition of D_n expresses with equation (3).

$$\vec{D}_n = \vec{N}_n \bullet \vec{T}_{n+1} = \left|\vec{N}_n\right|\left|\vec{T}_{n+1}\right| \cos\theta \quad (3)$$

Here N_n denotes the normal vector of point n, T_{n+1} denotes the vector of the cutting line n+1, and ● denotes the symbol of dot product, being the angle between N_n and T_{n+1}. As shown in Figure 7, this curve is equally divided into m points, in which the determinant of point i is the dot product value of the normal vector of the point i and the cutting line of point i+1. After calculation, it is known that $D_i < 0$, and the segment S_i is a convex curve. Similarly, the determinant of point j is the dot product value of the normal vector of the point j and the cutting line of point j+1. After calculation, it is known that $D_j = 0$, and the segment S_j is a straight line. The determinant of point k is the dot product value for the normal vector of point k and the cutting line of point k+1. After calculation, it is known that $D_k > 0$, and the segment S_k is a concave curve. The determinant of contour curvature can determine the concave or convex variations of the contour, which can be referential for the creation of lateral support.

Having acquired the contour of the maximum projection contour in Step 1, and defined the contour curvature in Step 2, the contour segment combination of the projection contour and the information of contour curvature can be achieved. Then, by using Step 3 below, the RP lateral support structure can be established for the insert, and the problem of positioning can be solved.

Step 3: Establishment of Lateral Support Structure

Through the above steps, the contour of the maximum projection contour can be analyzed from any insert type. For convenience sake, we can classify the contour of projection contour into three basic types: line type, curve type and hybrid type. The establishment of the support point is to find out from the determinant D_n the joint between two segments, divide the contour into several sets of segments, and finally establish lateral support structure at the middle points of various segments. Figures 8, 9 and 10 are the examples of the three basic contour types of the support structure. As the contour is circular, $D_n < 0$, and there is no variation or joint. Lateral positioning structure should be established at the three equally divided contour shapes, as shown in Figure 11.

2.3 Rules of Bottom Support of Insert

By means of the above-mentioned lateral support, the problems of lateral support and positioning of the insert are solved. Next, the paper discusses the bottom support problem of the insert. Having analyzed the outline curved surface of the insert, a support structure should be established on the geometric feature at the bottom of the insert. This support structure should reach the weight of the support insert, and achieve the effect of positioning. To establish the bottom support of the insert, there are three steps to be taken: effective visible surface definition, calculation of surface curvature of the insert, and determination of the position of bottom support point.

Step 1: Effective Visible Surface Definition

In the embedding process of the insert, in order to solve the interference problem between the insert and the RP object effectively, the visible surface in the embedding direction should be calculated. Suppose that a parallel light irradiates upward from the bottom of the insert, light shadow will appear on the surface of the insert, which should be the visible side in such direction. Taking a shaft with variable sectional area as an example, the visible surface, as shown in the figure 12, can be acquired after irradiation, which is known as the effective visible surface.

Step 2: Surface Curvature Definition of Insert

The aim of calculating "effective visible surface" is to determine the position of bottom support point. Take any random point P_n on the visible surface as the standard point, and find out the dot product of the normal vector N_n of this point (P_n) and the direction vector of the adjacent point (P_i), as shown in Figure 13.

The determinant of C_n is specified in the following equation:

$$C_n = \vec{N}_n \bullet \vec{L}_{n+1} = \left|\vec{N}_n\right|\left|\vec{L}_{n+1}\right|\cos\theta \tag{4}$$

From the above equation, the curvature C_n of any random point n on the surface of the insert can be obtained. As the point corresponds to the k adjacent points, if the determinant C_n is negative, and then this point is regarded as a convex point. If the determinant is positive, this point is regarded as a concave point. But if the determinant is zero, a plane surface will appear between this point and the adjacent point. The equation

Step 3: Determination of Bottom Support Position

Through the above definition, an effective visible surface can be analyzed at the bottom of any insert. After that, determinant C_n is used to find out the convex side, concave side and plane surface, and then the position of the bottom support point can be determined.

If it is judged to be a convex surface, an upward extending cup-shape support structure should be established from the lowest curve at the bottom, as shown in Figure 14. If it is judged to be a concave surface, a downward extending column-shape support structure should be established from the highest point of the depression, as shown in Figure 15. If it is judged to be a plane surface, no support structure is required.

By using the "rules of lateral support" and "rules of bottom support" proposed in this paper, the insert can be treated according to the following procedures so as to obtain its support structure, and achieve the objective of online manufacturing of insert imbedded. The procedures are indicated as follows:

1. Decide the embedding direction.
2. Find out the contour of the maximum projection contour.
3. Determine the curvature and the joint of the contour.
4. Construct lateral support structure.
5. Find out the effective visible surface.
6. Determine the curvature of surface.
7. Determine the bottom support point.
8. Construct the bottom support structure.

3. Conclusion

The online insert embedding process proposed in this paper is to solve the problems currently encountered in the SLA process when manufacturing complex geometric structure, functional mechanical structure and assembling object, such as the problems of laser shadowing, recoating interference, positioning and supporting, etc. The support of feature algorithm is developed in this paper. According to analysis and the future experimental results, online insert embedding process can effectively manufacture assembling object and insert to a satisfactory performance. In the future, the researcher intends to further the study into an in-depth investigation towards the deformity and size precision of insert at the RP object

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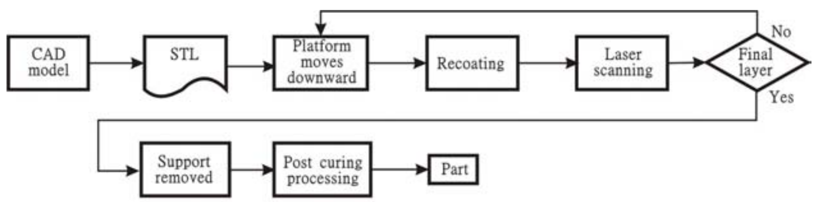


Figure 1. Flowchart of SLA Process.

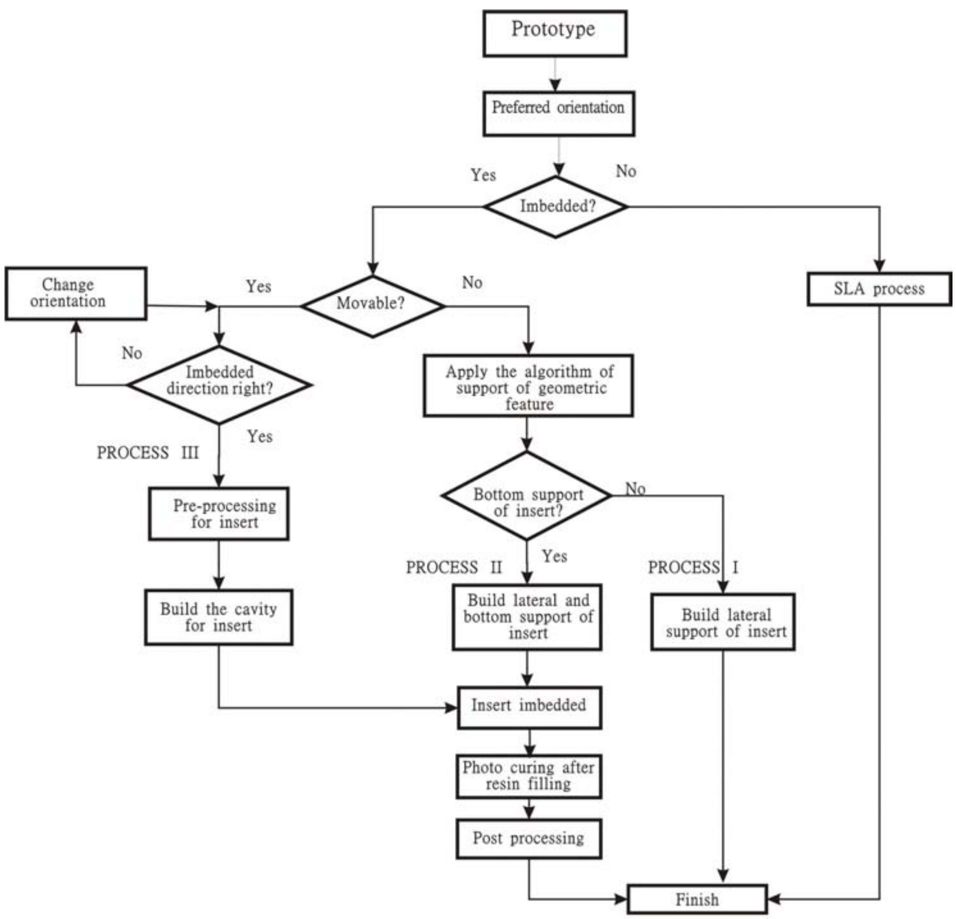
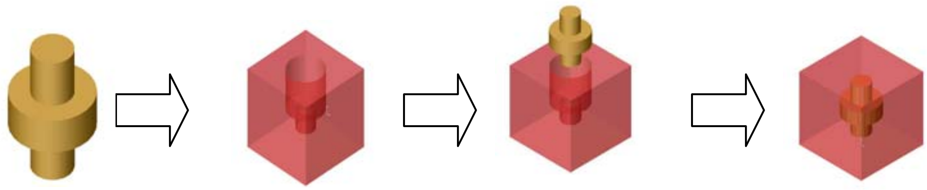


Figure 2. Flow Chart of Online Insert Embedding Process



(a) (b) (c) (d)

Figure 3. Schematic Diagram of Process 1. (a) Identify the feature of insert. (b) Establish RP object with cavity. (c) Embed the insert. (d) Pour in photo polymer and carry out post curing process.

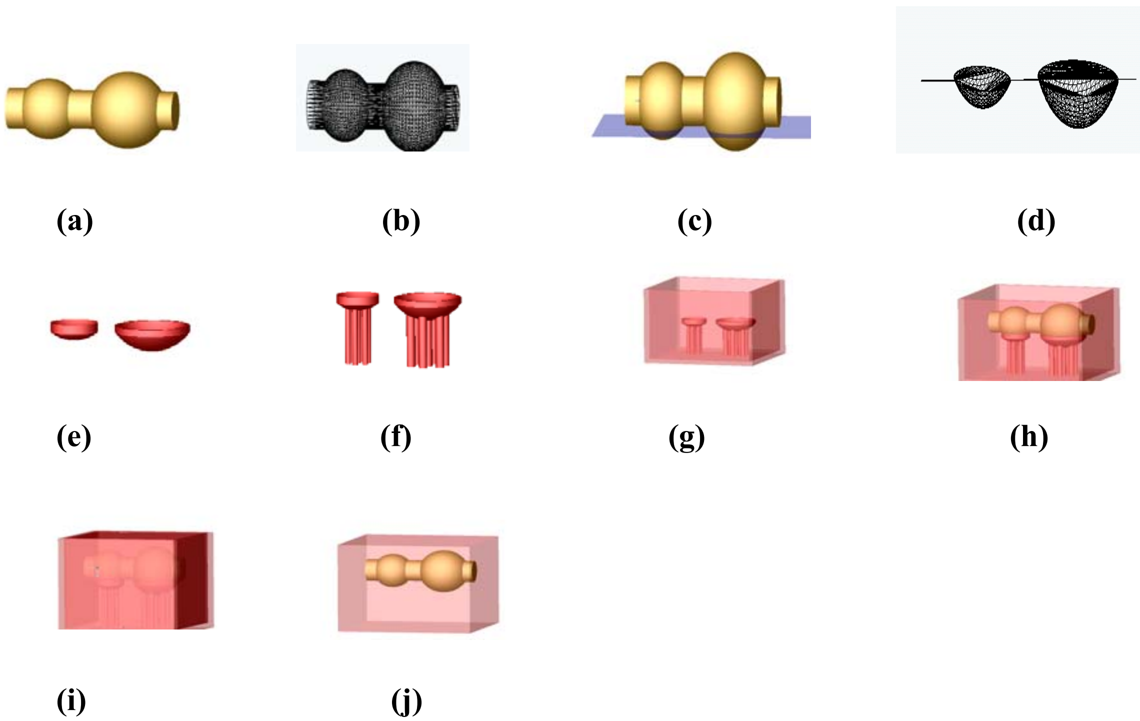


Figure 4. Schematic Diagram of Process 2. (a) evaluate the insert. (b) feature structure analysis. (c) the plane cut through the insert. (d) analyze the insert below the plane. (e) the support holder generate along the feature surface. (f) generate the support. (g) build the RP semi-part. (h) imbed the insert. (i) pour the resin and vacuum process. (j) post curing process.

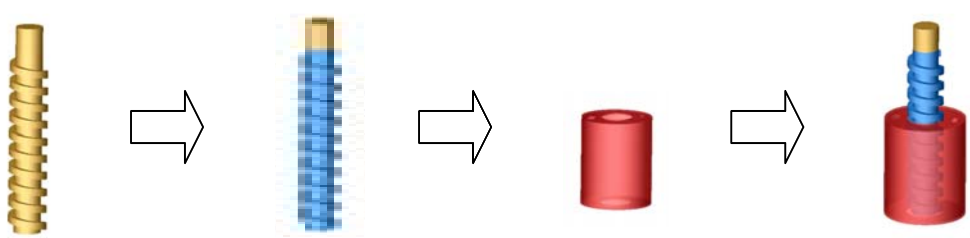


Figure 5. Schematic Diagram of Process 3.

Figure 6. (a) Parallel Light Projected to Insert in Embedding Direction. (b) Maximum Projection Side in Embedding Direction

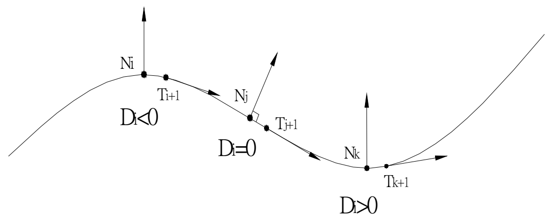


Figure 7. Determination of Curvature of Various Points on Curve

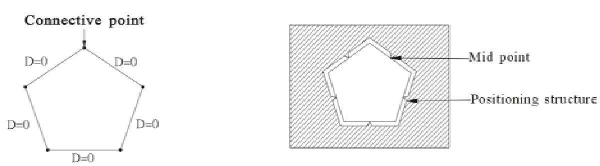


Figure 8. Line-Type Contour Insert and Lateral Positioning Structure

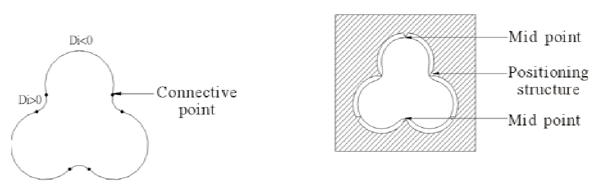


Figure 9. Curve-Type Contour Insert and Lateral Positioning Structure

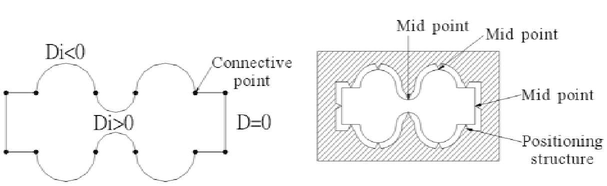


Figure 10. Hybrid-Type Contour Insert and Lateral Positioning Structure

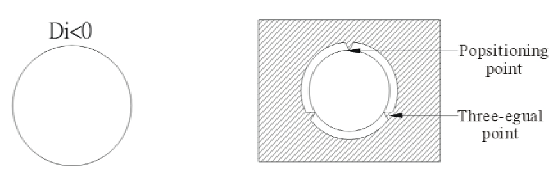


Figure 11. Variation-Free and Joint-Free Lateral Positioning Structure of Circular Section of Insert as $D_n < 0$

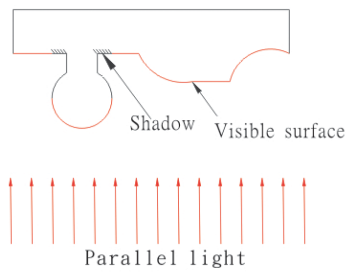


Figure 12. Upward Parallel Light Irradiation on Circular Shaft and Schematic Diagram of Visible Surface.

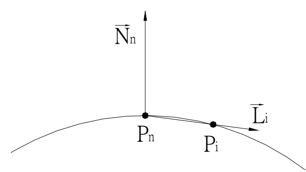


Figure 13. Illustrated Diagram of Dot Product of Vector N_n and Direction Vector L_i of Adjacent Point

Figure 14. Support Structure for the Convex Surface and the Bottom of the Insert

Figure 15. Support Structure for the Concave Surface and the Bottom of the Insert