Automated Generation of Layered Model for Surface Micro-machined MEMS

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ABSTRACT

A big obstacle for rapid development of MEMS devices is the cumbersome and unintuitive traditional MEMS design methodology. In recent years the structured design for MEMS has been paid more and more attentions. One key issue for achieving the structured design method is how to automatically generating layered model and mask layout. This paper proposes a novel approach for automatically generating the layered model from the geometric model of a surface micro-machined MEMS device. In the approach, process features are defined and classified for surface micro-machined MEMS, process features are automatically recognized from the geometric model, and the layered model is automated generated based on the recognized process features. Using this approach, MEMS designer can wholeheartedly concentrate on creative design activity without considering the tedious fabrication process.

Keywords: Process Feature, Feature Recognition, Layered Model, MEMS, CAD

1. INTRODUCTION

Although there are very sophisticated CAD tools for integrated circuits(ICs), most of them are not applicable to microelectromechanical systems(MEMS) due to their complicated 3D structures. Currently, to design a MEMS device, designers need to directly figure out its fabrication mask layout and process. In this way, designers can't concentrate on creative design activity and are required to be very familiar with fabrication knowledge. Obviously, as MEMS devices become more and more complex, it's almost impossible for designers to design them in such an unstructured manner.

The ideas about structured design for MEMS were proposed in 1996[4]. It could clearly separate MEMS design issues from fabrication, but its implementation in MEMS field faces two obstacles: one is the complicated multi-disciplinary nature of MEMS; the other is that the design and fabrication of MEMS are critically coupled together.

In this paper, a novel approach to layered model generation for surface micro-machined MEMS is proposed. With the approach, the layered model is automatically generated based on its geometric model created with traditional CAD system such as SolidWorks, UGII, Pro/E, etc. The objective of this work is to enable the separation of geometric modeling from processing planning of MEMS devices by automatically generating the layered model as well as the mask layout and process based on the geometric model of the MEMS device.

The other parts of this paper are organized as follows. Section 2 reviews the literature related to the topic. Some basic concepts and an overview of the approach are presented in section 3. Section 4 gives the definition of process features. Recognition of process features, construction of layered model and implementation are respectively described in section 5, 6 and 7. Concluding remarks are made in section 8.

2. RELATED WORK

Previous researches on MEMS device design methods mainly concentrate on how to effectively generate 3D geometric model and mask layouts of MEMS devices.

In general, there are two different approaches to construct 3D geometric models. One is to combine the fabricated mask layouts and process descriptions to simulate the result of fabrication, so called process simulation, and construct the 3D model of MEMS device eventually. OYSTER[16] and MemBuider[19] place emphasis on creating process simulations and 3D CAD models that could be used to predict the physical behavior of MEMS devices. MEMShapes[9], another 3D simulator, uses solid modeling techniques to build models of MEMS devices, and develops a process algebra that captures all the geometric and material transformations occurring to the MEMS device as it is fabricated. Hubbard etc., uses a crystal plane offset approach[13] and a cellular automata approach[12] to generate 3D models of MEMS devices fabricated using a bulk micromachining process with given masks. Directly constructing the 3D models using CAD tools is another approach. A feature-based geometric design tool for surface micro-machined MEMS[10-11] is developed, which enables designers to create fabrication-ready 3D models of MEMS devices in an intuitive manner. In addition, a feature-based methodology for reconstructing schematics from the layout information is presented [5-6].

Mask synthesis refers to automatically generating mask layouts based on the geometric model of a MEMS device. Currently there are two approaches to conducting it: one uses process simulation; the other is based on a parameterized layout model. It is attempted to synthesize the masks for a bulk-etched single layer with multiple etchants using genetic and evolutionary algorithms [14][18], which ensures the submitted design made by a specific process. Another effort tries to solve this problem by an algebraic approach [1-3][20]. However, the input of such approach is not a single model and couldn't be closely integrated with current CAD systems. Automated transfer of solid models into layout format is realized for the design of a micro gyroscope [7], which is not general.

3. BASIC CONCEPTS AND OVERVIEW

3.1 Basic Concepts

With surface micromachining, MEMS devices are built up by the deposition and etching of layers of materials [17]. The process starts with the substrate, then structural layers and sacrificial layers are generated, and finally the structural layers with materials such as polysilicon are reserved, whereas the sacrificial layers with materials such as PSG are released.

The followings are some definitions used in this paper, some of which are illustrated in Fig. 1.

Manufacturing Base Face (MBF): the top face of the substrate.

Manufacturing Direction (MD): the normal direction of MBF.

Vertical Face: a planar face whose normal is perpendicular to MD or a cylindrical face whose axis is parallel to MD.

Horizontal Face: a planar face whose normal is parallel to MD. Moreover, if the normal is same as MD, the face is called **upward face**; otherwise called **downward face**.

Upright Edge (UE): an edge belonging to a horizontal face.

Manufacturing Distance of UE: the distance between the edge and MBF.

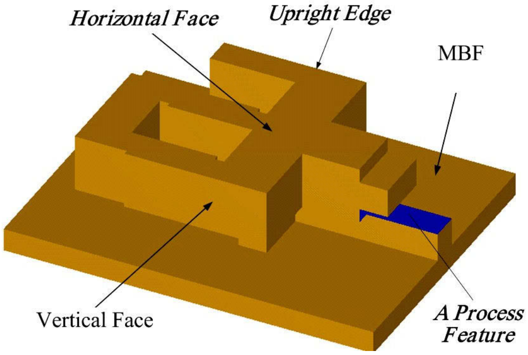


Fig. 1. Illustration of basic concepts

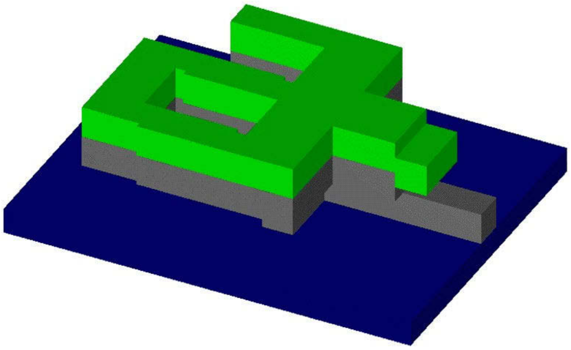


Fig. 2. Layered model of an actuator

Process Feature: a set of faces and edges that are closely related to manufacture process.

Layer: a set of affected parts by a single operation. A layer may contain several lumps.

Process feature Model: the model representing a MEMS device organized by process features that are recognized from the geometric model of MEMS device.

Layered Model: the model representing a MEMS device by layers. As an instance, the layered model of a simple actuator is illustrated in Fig. 2, where different colors mark different layers.

3.2 Overview of the Method

As the complexity of MEMS devices and the scope of MEMS application increases, the need for structured design methods is increasing. One key issue for achieving the structured design of MEMS devices is how to automatically generating the layered model and mask layout for a MEMS device after its geometric model is accomplished. By analyzing the intrinsic association between the geometric model and mask layout of a MEMS device, we observe that it is possible to generate the layered model and mask layout according to the geometric model of a MEMS device, and the process features play a key role in this process. With such

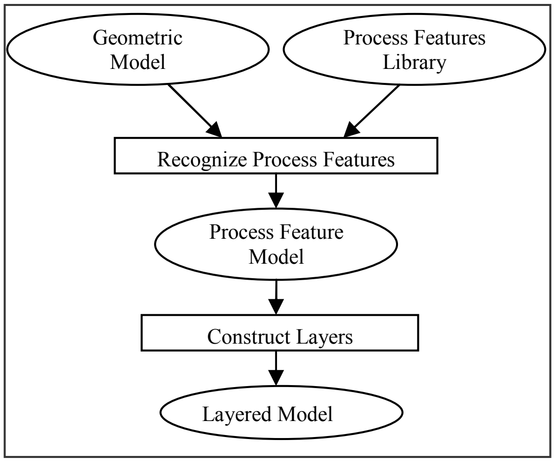


Fig. 3. Flowchart of the method

observation, we propose a method for automatically generating the layered model of a MEMS device according to its geometric model based on process features recognition. The flowchart of this method is given in Fig. 3. Here the research is focused on MUMPs (Multi-User MEMS Processes)[15] surface micromachining process.

4. PROCESS FEATURE CLASSIFICATION

Six kinds of process features are defined by analyzing the typical shapes appearing in micro devices and the special characteristic of MUMPs process. The abstraction of these features is strongly related to the fabrication process. Specifically, a process feature is represented as a chain of upright edges together with their adjacent faces, and it can be generally expressed as follows:

$$PF_{\text{feature}}=C_H\{E,F\} \tag{1}$$

Here, E refers to a set of upright edges $\{E_n(t)\}$. F represents a set of faces $\{F_{nm}(t)\}$. H represents the thickness of the feature. $E_n(t)$ is an upright edge, here t refers to the convexity of the edge (c, concave; v, convex), and the subscript n is the serial number of the edge in the chain. $F_{nm}(t)$ refers to a face, here t refers to the face type (d, downward face; v, vertical face; u, upward face), and the subscript n and m refer to the serial numbers of its two adjacent edges (if n or m is x, the corresponding edge has no exact serial number).

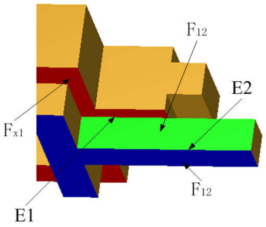


Fig. 4. Illustration of BEND

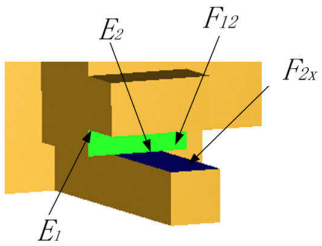


Fig. 5. Illustration of SIDE POCKET

(1) BEND

BEND feature is defined as:

$$PF_{\text{BEND}}=C_H\{E,F\} \tag{2}$$

where

$$E=\{E_1(c),E_2(v)\}$$

$$F=\{F_{x1}(d),F_{12}(v),F_{2x}(d)\}$$

$$H=\text{Dist}(E_1,MBF)-\text{Dist}(E_2,MBF)$$

Dist(t,f) is the distance between edge t and face f. According to the distance to the MBF, $F_{x1}(d)$ is called top face, $F_{12}(v)$ is called middle face, and $F_{2x}(d)$ is called bottom face of BEND feature.

Fig. 4 shows a BEND feature instance, where MD is opposite to the normal of F_{x1} .The engineering semantic of BEND feature is that below its faces there should be a sacrificial layer.

(2) SIDE POCKET

SIDE POCKET feature is defined as:

$$PF_{\text{SIDE POCKET}}=C_H\{E,F\} \tag{3}$$

where

$$E=\{E_1(c),E_2(c)\}$$

$$F=\{F_{x1}(d),F_{12}(v),F_{2x}(u)\}$$

$$H=\text{Dist}(E_1,MBF)-\text{Dist}(E_2,MBF)$$

According to the distance to the MBF, $F_{x1}(d)$ is called top face, $F_{12}(v)$ is called middle face, and $F_{2x}(u)$ is called bottom face of SIDE POCKET.

Fig. 5 shows a SIDE POCKET feature instance, where MD is opposite to the normal of F_{2x} and F_{x1} is not showed. The engineering semantic of SIDE POCKE is that between its faces there should be one or several sacrificial layers.

(3) STEP

STEP feature is defined as:

$$PF_{STEP}=C_H\{E,F\} \tag{4}$$

where

$$E=\{E_1(v),E_2(c)\}$$

$$F=\{F_{x1}(u),F_{12}(v),F_{2x}(u)\}$$

$$H=\text{Dist}(E_1,MBF)-\text{Dist}(E_2,MBF)$$

According to the distance to the MBF, $F_{x1}(u)$ is called top face, $F_{12}(v)$ is called middle face, and $F_{2x}(u)$ is called bottom face of STEP.

Fig. 6 shows a STEP feature instance, where MD is same as the normal of F_{x1}. The engineering semantic of STEP is that between its faces there isn't a sacrificial layer.

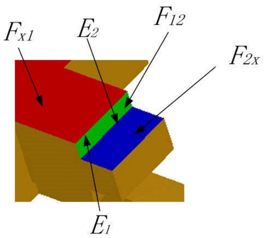


Fig. 6. Illustration of STEP

(4) SIDE PROTRUSION

SIDE PROTRUSION feature is defined as:

$$PF_{\text{SIDE PROTRUSION}} = C_H\{E,F\} \tag{5}$$

where

$$E = \{E_1(v), E_2(v)\}$$

$$F = \{F_{x1}(u), F_{12}(v), F_{2x}(d)\}$$

$$H = \text{Dist}(E_1, MBF) - \text{Dist}(E_2, MBF)$$

According to the distance to the MBF, $F_{x1}(u)$ is called top face, $F_{12}(v)$ is called middle face, and $F_{2x}(d)$ is called bottom face of SIDE PROTRUSION.

Fig. 7 shows a SIDE PROTRUSION feature instance, where MD is same as the normal of Fx1. The engineering semantic of SIDE PROTRUSION is that between its faces there maybe a structural layer.

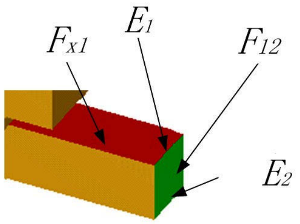


Fig. 7. Illustration of SIDE PROTRUSION

(5) FIXING POCKET

Feature FIXING POCKET is defined as:

$$PF_{\text{FIXING POCKET}} = C_H\{E,F\} \tag{6}$$

where

$$E = \{E_1(v), E_2(v), E_3(v), E_4(v)\}$$

$$F = \{F_{12}(d), F_{23}(v), F_{34}(u), F_{41}(v)\}$$

$$H = \text{Dist}(E_1, MBF) - \text{Dist}(E_4, MBF)$$

According to the distance to the MBF, $F_{12}(d)$ is called top face, $F_{23}(v)$ and $F_{41}(v)$ are called middle faces, and $F_{34}(u)$ is called bottom face of FIXING POCKET.

Fig. 8 shows a FIXING POCKET feature instance, where MD is same as the normal of F_{34}. The engineering semantic of FIXING POCKET is that among its faces those are used to constrain other body only to rotate.

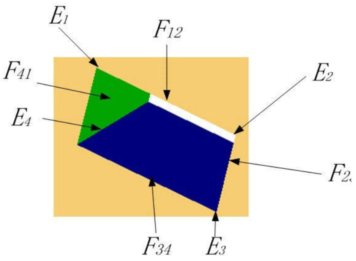


Fig. 8. illustration of FIXING POCKET

(6)DIMPLE

DIMPLE feature is defined as:

$$PF_{\text{DIMPLE}} = C_H\{E,F\} \tag{7}$$

where

$$E = \{E_1(c), E_2(v), E_3(v), E_4(c)\}$$

$$F = \{F_{x1}(d), F_{12}(v), F_{23}(d), F_{34}(v), F_{4x}(d)\}$$

$$H = \max(\text{Dist}(E, F_{x1}(d)))$$

and $F_{x1}(d)$ and $F_{4x}(d)$ are coplanar.

According to the distance to the MBF, $F_{x1}(d)$ are called top face of DIMPLE. Fig. 9 shows a DIMPLE feature instance, where MD is opposite to the normal of F_{x1}. The engineering semantic of DIMPLE is that its tiny faces are used to decrease friction between bodies. There is another type of DIMPLE feature (sharp DIMPLE) is similar to above DIMPLE. Sharp DIMPLE feature has one more face and one more convex edge between E2 and E3.

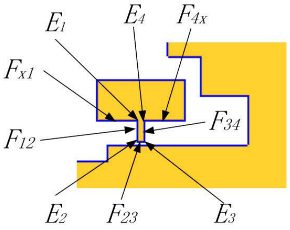


Fig. 9. Illustration of DIMPLE (cross section)

5. RECOGNITION OF PROCESS FEATURES

Based on the above definitions of process feature, we develop an algorithm for automatically recognizing process features from the geometric model of a MEMS device.

5.1 Preprocessing of the Geometric Model

Before feature recognition, the geometric model of the MEMS device needs to be preprocessed first to determine assembly constraints and MBF.

5.1.1 Determination of Assembly Constraints

If there are at least two bodies in the geometric model of MEMS device, it is necessary to determine assembly constraints, master body and secondary bodies. The constraints are classified as both-direction constraint, upward constraint and downward constraint. A both-direction constraint constrains both rotation and translation, while an upward constraint only constrains upward motion and a downward constraint just constrains downward motion. The master body as well as constraints is currently determined interactively.

5.1.2 Determination of MBF

It is obvious that the substrate is between its bottom face and MBF, and it is a sweeping body. We determine the MBF as follows:

(i) Sort planar faces of the master body by their area in descend and put all face pointers in a face pointer array.

(ii) For each face (F1) in the array, find out another planar face (F2) in master body that is the closest parallel face to F1, and split the master body into two bodies using F2's supporting plane. If the body including the F1 is a transform-sweeping body, the face F2 is MBF and the process end, otherwise continue with the next face in the array.

5.1.3 Removing of the substrate

Split the master body into two parts with the supporting plane of the MBF. The part above the MBF is marked as the new master body, and the other part becomes the substrate. The new master body is composed of structural layers. The new bottom face in new master body is called a contacted MBF, and it is also recorded.

5.2 Automated Recognition of Process Feature

Our algorithm for automated recognition of process features consists of four steps. Fig. 10 shows the flowchart of the algorithm.

(1) Construction of upright edge link for master body

A link of upright edges (LUE) is first established for the master body. For each edge in master body, if it is an upright edge, it will be added to LUE, and its convexity and state (used/unused) are also recorded 'unused'.

(2) Recognition of FIXING POCKET

In LUE, firstly find out all edge pairs where there are two 'unused' parallel concave edges in the same face in each pair. For each pair (the two edges are denoted by E1 and E2), verify E1 and E2 'unused'; find out E1's coplanar 'unused' parallel concave edge (E3) that is different from E2; and find out E2's parallel 'unused' concave edge that is different from E1. If succeed and E3 and E4 are in the same face, a FIXING POCKET is recognized. And set all four edges 'used'. If finding operation or verifying operation doesn't succeed, continue with the next pair until all pairs are handled.

(3) Recognition of BEND, SIDE POCKET, STEP and SIDE PROTRUSION

For each 'unused' edge (E1) in LUE, set the state of the edge 'used' firstly, and find an 'unused' edge (E2) from its adjacent vertical face. If the manufacturing distance of E1 is greater than that of E2, E1 and E2 are exchanged in order to keep E1 above E2 along MD.

Determine whether the edge pair (E1, E2) as well as their adjacent faces constitute a process feature as follows: If both E1 and E2 are concave, and the adjacent horizontal faces of E1 and E2 are a downward face and an upward face respectively, a SIDE POCKET is recognized; if E1 is concave and E2 is convex, and the adjacent horizontal faces of E1 and E2 are both downward faces, a BEND recognized; if E1 is convex and E2 is concave, and the adjacent horizontal faces of E1 and E2 are both upward faces, a STEP is recognized; if both E1 and E2 are convex, as well as the adjacent horizontal faces of E1 and E2 are an upward face and a downward face respectively, a SIDE PROTRUSION is recognized.

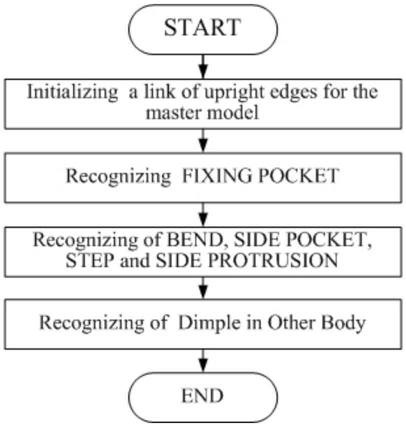


Fig.10. Flowchart of automatic recognition of process features

The above steps will be carried out again for another edge in LUE until there is no 'unused' concave edge in LUE.

(4) Recognition of DIMPLE

For each secondary body, the LUE is constructed in the same way, and the recognition of DIMPLE is based on the LUE. For each 'unused' concave edge (E1) in the LUE, all concave edges (E2) disconnecting with E1 are put in a special edge set. If the set is not empty, a series of steps are done as follows.

(i) If the secondary body can be spilt into two bodies by a face whose boundaries are two edges in the set, and all edges in the down part (T1) are convex, transfer to step (ii); otherwise go to step (iv).

(ii) If their adjacent vertical faces are parallel or concentric, the distance between the two faces is calculated. And if the distance is less than a threshold, a DIMPLE is recognized.

(iii) The thickness of the DIMPLE feature is set as the distance that is the largest one between each of all the vertices and the split plane in T1.

(iv) All edges in the set are set 'used'.

If no DIMPLE is recognized, the above steps will be carried out again for another edge in LUE until there is no 'unused' concave edge in LUE.

All recognized features form a process feature model of the MEMS device.

6. CONSTRUCTION OF LAYERED MODEL

When a process feature model has been built, a layered model of a MEMS device can be constructed based on it. A layered model consists of all layers used to fabricate the MEMS device, including structural layers (called POLY0, POLY1 and POLY2), released sacrificial layers (called OXIDE1 and OXIDE2), substrate and mental layer (not considered in this paper because its function doesn't like other layers).

According to the definition and classification of the process features for MUMPs process as well as the particularity of MUMPs Process, the different features should belong to different layers. POLY0 can only be associated with SIDE PROTRUSION whose bottom face is a contacted MBF. POLY1 or POLY2 can be associated with SIDE POCKET that must be shared by other structural layer, and can be solely associated with SIDE PROTRUSION, STEP and BEND. POLY2 can also be associated with FIXING POCKET. A DIMPLE should associate with secondary body belong to POLY1 or POLY2. The features associating with sacrificial layers are SIDE POCKET, BEND and FIXING POCKET.

Based on above abstraction, we develop following concepts and algorithm.

6.1 Layered Feature

Before defining layered feature, we first introduce the definition of covering relationship and equivalent face.

6.1.1 Covering Relationship

Supposing *M* and *N* are bodies or face lists, a **covering relationship** between *M* and *N* exists if the following conditions are satisfied:

(i) *M* disconnects with *N*;

(ii) If there is a face (F1) in *M* whose projection onto MBF overlay the projection of one or more face (F2) of *N*, the distance between F1 and MBF must be greater than that between F2 and MBF.

(iii) There is at least one face (F1) in M whose projection onto MBF overlay the projection of one or more faces (F2) in *N*, and the distance between F1 and MBF is greater than that between F2 and MBF.

Here, *M* is called a covering body or face list, and *N* is called a covered body or face list. A face list is used to check the covering relation is called a covering-related face list (CFL). As an example, a face list A composed of f1, f2 and f3 has a covering relationship with body T1, but has no covering relationship with body T2 in Fig. 11.

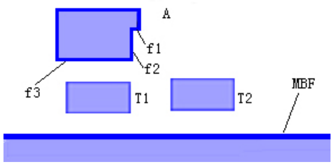


Fig. 11. Covering relationship (Cross Section)

6.1.2 Equivalent Face

If the supporting plane of a feature's bottom face intersects with the master body, split the master body using the supporting plane, and create a serial of new faces. Among those faces, a downward face adjacent to the middle face of the feature is called an **equivalent face** of the feature. The engineering semantic of the equivalent face is that it together with the middle face and bottom face of the feature constitutes a CFL of the feature.

In Fig. 12, face f4 is the equivalent face of SIDE POCKET SP1, and face f8 is the equivalent face of SIDE POCKET SP2. Obviously, between the two face lists composed of the top face, middle face and equivalent face of SP1 ad SP2, there is a coving relationship. However, there is no covering relationship between the two face lists consisting of the top face, middle face and bottom face of SP1 and SP2.

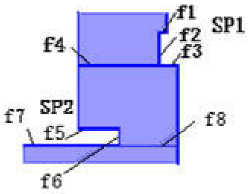


Fig. 12. Equivalent face (Cross Section)

6.1.3 Layered Feature

Layered feature refers to the process feature that indicates the existing of some sacrificial layer. For example, SIDE POCKET is a typical layered feature whose middle face, top face and bottom face are in different layers.

It is observed that for the BEND feature, if its bottom face is a contacted MBF, it is actually a SIDE POCKET whose bottom face is on MBF and is cut off in the preprocessing of recognition algorithm to form a new bottom face (It is an actually equivalent face). Similarly for the FIXING BOX feature, it can be regarded as the combination of two symmetric SIDE POCKET features. Thus that kind of BEND, FIXING POCKET features can be considered as special SIDE POCKET feature.

So SIDE POCKET is a vital feature, and its thickness can be divided into four cases:

(i) It equals the thickness of some sacrificial layer;
(ii) It equals the total thickness of two sacrificial layers;
(iii) It equals the total thickness of two sacrificial layers and a secondary body;
(iv) It shows a transitional length of a sacrificial layer.

If case (iv) appears, there must be another SIDE POCKET whose bottom face is identical with that of the former SIDE POCKET, and the thickness of latter SIDE POCKET belongs to one of other three cases. The CFLs of layered features are used to determinate the covering relationship between themselves and secondary bodies to get which layer their middle and top faces belongs to and which layer their bottom face belongs to.

6.2 Algorithm

The main idea for constructing the layered model of a MEMS device based on the recognized process features includes three points:

- For a simple structural layer (such as POLY0, POLY1), find out sweeping faces first based on layered features, then determine the thickness using SIDE PROTRUSION, finally perform a sweeping operation with the determined sweeping faces and thickness to get the layer.
- For a complicated layer (such as POLY2), perform a Boolean subtract operation upon the master body and the generated simple layers (such as POLY0, POLY1) to get it.
- For sacrificial layers, find out sweeping face list first based on some conditions, then determine the thickness from layered feature, finally perform a sweeping operation with the determined sweeping faces and thickness to get the layer.

To record the same layer information shared by different process features, here **a strong couple relationship** between features is given if there are same top face and bottom face or the same middle face and bottom face between two features. Moreover a **FEATURE-GROUP** structure is defined and used to manage the features with strong couple relationships between them. This structure contains an array of feature's pointers, a top-middle face list, a bottom face list, an equivalent face list, and two ownership values of top-middle face and bottom face.

The input of this algorithm is MBF, the geometric model and recognized process features of a MEMS device. The whole flowchart of algorithm is illustrated in Fig. 13 and described in detail as follows.

(i) Grouping layered features

Based on the continuity of materials in process, layer features with strong couple relationships between them are grouped into a FEATURE-GROUP. Moreover, for the BEND feature whose bottom face is not a contacted MBF, it should be added into the FEATURE-GROUP in which there is a feature whose top face is identical with the bottom face of the BEND feature.

For each FEATURE-GROUP, the faces of every feature in the FEATURE-GROUP are managed. Top face and middle face are added into the top-middle face list, bottom faces are added into the bottom face list (if the feature is not a BEND) or the equivalent face list (if the feature is a BEND), and equivalent face is added into the equivalent face list (if the feature is not a BEND). The CFL of FEATURE-GROUP is composed of one's top-middle face list and equivalent face list.

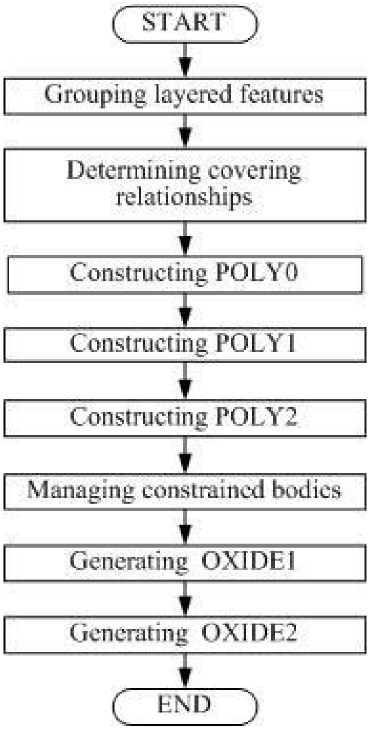


Fig.13. Flowchart of constructing layered model

(ii) Handling covering relationships in all FEATURE-GROUPs.

Handle those FEATURE-GROUPs gotten in step (i) by using their CFLs to get the sweeping faces of layers.

Check covering relationship between every two CFLs of those FEATURE-GROUPs. If there is a covering relationship and the CFL of one FEATURE-GROUP is 'covered', then the ownership of the top-middle face list of the FEATURE-GROUP is POLY1, and the ownership of the bottom face list is POLY0 (or substrate). And if there is a covering relationship and the CFL of one FEATURE-GROUP is 'covering', then the ownership of the top-middle face is POLY2 and the ownership of the bottom face is POLY1.

If there is not a covering relationship between a few of CFLs of FEATURE-GROUPs, check a covering relationship between each of those CFLs and each of secondary bodies. The same operation is done for CFLs of FEATURE-GROUP as showed in step (i). If one secondary body is 'covered', it should be added into the solid list of POLY1, and marked 'used'; and if one secondary body is 'covering', it should be added into the solid list of POLY2, and marked 'used'.

As shown in Fig. 12, two FEATURE-GROUPs are constructed with two SIDE POCKETs. And there is a covering relationship between the CFLs of SP1 and SP2. The CFL of SP1 is 'covering', so the ownership of top-middle face list in SP1's FEATURE-GROUP is POLY2, and the ownership of bottom face list in SP1's FEATURE-GROUP is POLY1. The CFL of SP2 is 'covered', so the ownership of top-middle face list in SP2's FEATURE-GROUP is POLY1, and the ownership of bottom face list in SP2's FEATURE-GROUP is POLY0 (or substrate).

(iii) Constructing the first structural layer POLY0

For each FEATURE-GROUP, if the ownership of the bottom face list is POLY0, all the bottom face in the list are the upper faces of POLY0, and are added to a temporary face list. Moreover, for each face in the temporary face list, if it is identical with the top face of a SIDE POTRUSION whose bottom face is a contacted MBF, the bottom face is appended to the sweeping face list of POLY0 and the thickness of this SIDE POTRUSION is taken as the thickness of POLY0. Furthermore, if there is a SIDE POTRUSION whose bottom face is not identical with that of one BEND, the bottom face of the feature is also added to the sweeping face list of POLY0.

After the redundant faces are removed from the sweeping list of POLY0, perform a sweeping operation with the determined sweeping faces and thickness to get the master body of POLY0.

(iv) Constructing the second structural layer POLY1

For each FEATURE-GROUP, if the ownership of its top-middle face list is POLY1, the top-middle face list and the equivalent face list are added into the sweeping face list of POLY1. If the ownership of its bottom face list is POLY1, i.e., all the faces in the bottom face list are the upper faces of the POLY1, all faces are added into a temporary face list.

For each face in the temporary face list, if it is identical with the top face of a SIDE POTRUSION whose bottom face is in the sweeping face list of POLY1, the thickness of the SIDE POTRUSION is taken as that of POLY1.

After the redundant faces are removed from the sweeping list of POLY1, perform a sweeping operation with the determined sweeping faces and thickness to get the master body of POLY1.

(v) Constructing the third structural layer POLY2

Perform a Boolean subtract operation upon the master body of geometric model and the master bodies of POLY0 and POLY1, and the result is the master body of POLY2.

(vi) Handling secondary bodies

If a secondary body is not marked 'used', handle it based on constraint set up in section 5.1. If the constraint imposed on the body is a both-direction constraint and or an upward constraint, the body belongs to POLY1, as far as MUMPs is concerned. If the constraint is a downward constraint and the body is above one solid of POLY1, the body should belong to POLY2. If the constraint is a downward constraint, the body is not above one solid of POLY1, and the thickness of the body is equal to that of POLY1, the body belong to POLY1, and if the thickness of the body is greater than that of POLY1, split the body into an upper part and an downward part using the face parallel to the bottom face of the body with the distance equal to the thickness of POLY1, and add the upper part and the downward part into the solid list of POLY1 and POLY2 respectively (they are called coupling bodies)

Now the output of the algorithm is a layered model with substrate and three structural layers.

(vii) Constructing the first sacrificial layer OXIDE1

The thickness of all sacrificial layers is calculated from layered features and the ownerships of the faces. It is done in step (i) and (ii). The sweeping faces list of OXIDE1 is found out based on an intermediate model constructed by the bodies in POLY0 and substrate. The intermediate model refers to an existing model whose upper face will be affected in following operation during fabrication. A face in the intermediate model can be added to the sweeping face list of OXIDE1 if it satisfies one of the following conditions:

a) The face is an upward face, and it is exposed completely or partly in the geometric model;
b) The face is a vertical face, and its two adjacent faces satisfying condition (a), and two common edges among the final face and its two adjacent faces are on the edges of the geometric model.

After the sweeping faces list is established, perform a sweeping operation with the determined reverse sweeping faces and thickness to get the unchecked master body in the solid list of OXIDE1 layer.

(viii) Removing the redundant part of the unchecked solid of OXIDE1

If there is a secondary body in POLY1, it must be made by the release of OXIDE1 during fabrication, and the body should contacts the upper face of OXIDE1, so it should be moved to the right position by shift transformation. The shifting distance depends on whether a body contains a DIMPLE feature. If so, the distance will be the thickness of OXIDE1; otherwise it is the difference between the thickness of OXIDE1 and the thickness of DIMPLE. Moreover, perform a Boolean subtract operation upon the geometric model and the body of OXIDE1 to remove the overlap between them. For the POLY2, if there is a secondary body whose coupling body is transformed, it should be transformed also in this step.

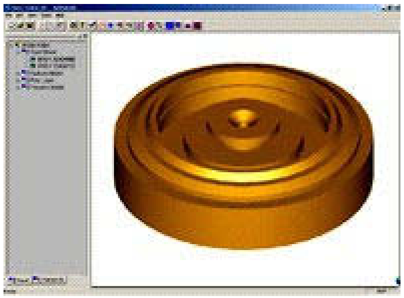
(ix) Generating the second sacrificial layer OXIDE2

The generation of OXIDE2 is similar to that of OXIDE1.

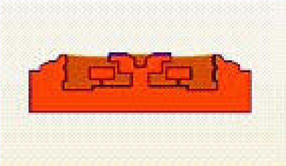
The final output of the algorithm is a layered model with a substrate, three structural layers and two sacrificial layers.

7. IMPLEMENTATION

The algorithm presented in this paper has been implemented with Visual C++ based on the geometric modeling kernel ACIS6.0. A tested example is given in Fig. 14-16.



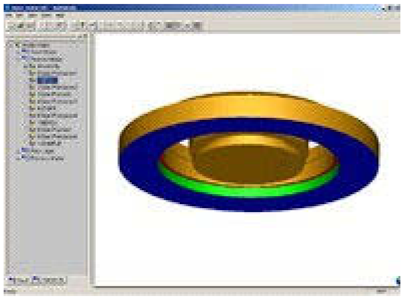
a. 3D view



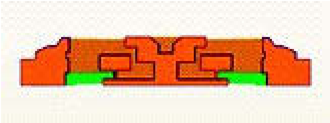
b. A cross section along MD

Fig.14. The geometric model of the micro-motor

Fig. 14 shows the geometric model of micro-motor, which is designed with SolidWorks (a common CAD system). Fig. 15 illustrates a process feature (a BEND). Here red face, green face and blue face belong to the BEND feature, and the red face is top face, the green face is middle face, and the blue face is bottom face (it is a contacted MBF). Fig. 16 gives the final layered model. Here the blue body belongs to substrate, red body belongs to POLY0, gray body belongs to POLY2, orange body belongs to OXIDE1, and fuchsia body belongs to OXIDE2.

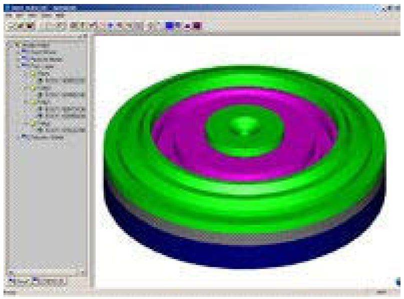


a. Process features tree and 3D view

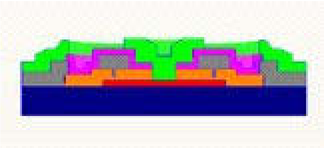


b. A cross section along MD

Fig. 15. The process feature model of the micro-motor



a. 3D view



b. A cross section along MD

Fig 16. The final layered model of the micro-motor

8. CONCLUSION

In this paper, a method of generating layered model from geometric model for surface micro-machined

MEMS is proposed. The main contributions of this work include following three aspects:

- The process features for surface micro-machined MEMS are defined and classified.
- An approach to automated generation of the layered model of a MEMS device based on the recognized process features is given.
- Explore the possibility of developing structured MEMS device design methods.

The future work will focus on the manufacturability evaluation of layers and the improvement of algorithm efficiency.

9. ACKNOWLEDGEMENT

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