Technology of WAVE and Feature Cutter Volume of Manufacturing

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***Abstract*—A forward and automatic method for in-process model generation is proposed and integrated with three-dimensional computer aided process planning (CAPP) system. The method based on feature cutter volume of manufacturing drives the in-process model to evolve from blank to part, which is coincident with the manufacturing process and ideology of process design. At the same time, technology of What-if Alternative Value Engineering (WAVE) is implanted in the generation to establish the relationship of in-process models, which supports function of the automatic update for models. The paper introduces a theory of the solution to demonstrate the connection between manufacture feature and feature cutter volume, and detailedly presents the technological process in applying the WAVE technology. Examples are completed in a commercial CAPP system to illustrate the feasibility of this approach.**

***Index Terms*—CAPP, in-process model, manufacture feature, UG/WAVE, automatic annotation**

I. Introduction

With the development of three-dimension computer aided design (3D CAD) technology in the design field and manufacturing enterprises, the pattern of computer Aided Process Planning (CAPP) have already changed fundamentally. The manufacturing enterprises are looking forward a low-cost and efficient method to manufacture [1]-[2]. The integration of CAD/ CAPP/ CAM with automated workflow can shorten production cycle and achieve the aims of manufacturing companies. The automatical formation of in-process models in 3D environment is one of the most important technologies in the domain of CAD/CAPP/CAM integration. Process information based on 3D digital model ensure the consistency and accuracy in the process of product digital manufacturing [3]. Model-Based Definition [4]-[5] (MBD) technology is the main method to express the 3D digital Model, which integrates the information of the design product, such as the geometrical data, the dimensional tolerance, the machining datum, etc. [6]-[8] The way taking the integration of 3D digital model as the only basis for the manufacturing process, changes the traditional description method, which is relied mainly on digital quantity (digital model) while analogy quantity (the process information based on 2D sketch) subsidiary. The MBD model solves the problems taken by 2D CAPP pattern, such as tediously data input, dependent data between design and manufacturing. The 3D digital model provides a good foundation for information and intelligence of process planning [9].

The 3D in-process models in the process planning bridge the design and manufacture and reflect the changes of product shape and process information in different stages of the machining process [10]. Aided with the application of CAD, the process engineers generally create the in-process models for different machining steps through the process documents in CAPP. Zhou et al. [11] adopted manual methods to build in-process model such as deleting and modifying features on part model, and inserting features into part model. However, if the in-process models are modelled in manual, it will be a hard work, especially in the complex machining process. This pattern is inefficient and increase the enterprises' cost. What's more, it depends on the process engineers' experiments in modelling. To improve the efficiency of modelling in-process model, an automatical method is essential to help process engineer to build the in-process models. So far, the researches bout the automatically solving of the in-process model continue to be mature a. Dou Shasha [12] proposed a kind of rapid-generation for the topical processing based on UG_WAVE technology. Mohan and Shunmugam [13] used the application of CAD to simulate generation of machining process, generating intermediate models. But dealing with the complex parts and the transformed model, the method is not very convenient. Jianxun Li [14] proposed a method to automatic generating in-process models based on feature working step and feature cutter volume. It can solve the in-process model for the part with recognizable features very well, but for the part with unrecognizable features, it doesn't work efficiently.

All the methods mentioned above are c to modelling the corresponding accurate in-process models for the machining process. The applications based on feature reorganization and WAVE technology are the most mature methods. Though they are not perfect for all case, but they provide many good ideas for building in-process model.

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II. The Overall Scheme of Building In-Process Model

A. The Concept Related with In-Process Model and Idea of Current Solution

In the machining process of parts, the working procedure accords to the planned process route. After the end of every process, an intermediate state workpiece will be formatted, as a foundation for the next process. These intermediate state workpiece models are referred to as in-process model. In the full three-dimensional digital process planning, the three-dimensional process model as a carrier of the process information, eventually guides the parts' formatting [15].

At present, according to the direction of evolution, the methods of building in-process model basically have the following two kinds of solution.

1) Reverse generating method, evaluating from the part design model to blank model

A typical scheme is Teamcenter, a process planning Software published by Siemens PLM Software. The main idea takes advantage of function of WAVE (What-if Alternative Value Engineering) in CAD. At first, part design model is copied to every part component in every process, and then the synchronous modelling technology, which based on the structure of B-Rep, is used to modify corresponding features, such as remove, move, offset, etc. These operations will be automatically associated with the follow-up in-process model. Finally, blank model and intermediate state model are generated.

2) Forward generating method, evovlution from blank design model to part design model

This method is based on the designed blank model, taking advantage of function of Boolean computing in CAD. The idea is coincident with the manufacturing process and ideology of process design. Actually, there are some studies about this method. This paper discusses the generation method of in-process model based on technology of WAVE and delta-volume of manufacturing feature. The new modelling method combines manufacturing feature and UG/Wave function, and has strong operability and flexibility in engineering applications.

B. In-Process Model Automatically Generate Scheme Analysis

Since the In-process models express the intermediate state of mechanical processing and are taken as a carrier of the digital information in the whole process planning system, the generation is the core content of the whole system. As shown in Fig. 1, the solution takes the planning of information as input, combines with a certain technology and outputs the in-process model corresponding the process routine to realize the whole process planning system. As mentioned above, this paper is based on the structured process of manufacturing information, combined with technology of WAVE and delta-volume of manufacturing feature, effectively to generate the in-process model supporting WAVE technology.

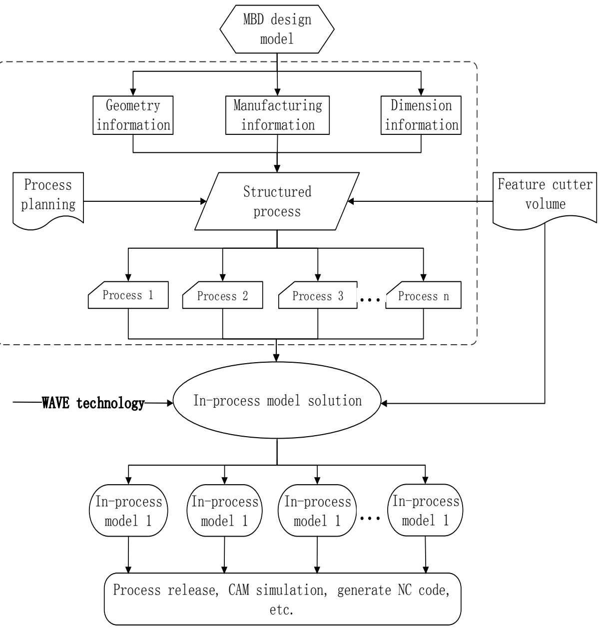

Figure 1. The overall scheme of building in-process model

III. Theory of Solving In-Process Model

A. Process Model to Solve Technical Related Concepts

1) Manufacture feature

Manufacture feature is a set of reflecting process constraints and a collection of feature information, which having the certain machining shape [16]. In-process of identifying the feature on the part design model based on the manufacturing process, the procedure groups the surfaces which has a certain process semantics and meet a certain process constraints on the part design model. To extract and calculate these surfaces data, the system can get the attribute parameter about manufacturing feature. So manufacturing feature is the basic unit for researching the integration system of CAD/CAM/CAPP.

2) Feature cutter volume

In parts of machining process, one process corresponds to at least one manufacturing feature. Feature Cutter refers to volume which would be removed from the workpiece to form some kind of manufacturing features. The volume having consistent structure on geometry is designed a kind of model which can be derived by parameters. Then procedure can instantiate feature cutter volume with parameter extracted from manufacturing feature.

3) The WAVE technology

The WAVE (what-if the Alternative Value Engineering) technology is lunched by UG (Unigraphics NX), to implement the technology of modelling between related components [6], which can design a new part based on geometry information and spatial location of the existing part, it is different from parameterized modelling technology, which only have the link between the features within a single par. WAVE technology can establish connection between different parts about geometry information so that subsequent components can be automatically updated when the parent components modify.

The in-process models generated by WAVE technology are inheritance relations, so the child process model can be automatically updated with the change of the parent process model.

B. *The Technical Principle Analysis about Generating In-Process Model*

In-process model can describes parts machining process, the mathematical expressions as shown below:

$$ProModel_{n_i} = PartBlank - \sum_{i=1}^{n_i} \sum_{k=1}^{m_k} FC_{ij} \quad (1)$$

$ProModel_{n_i}$ is a process model generated after the *i-th* process, $PartBlank$ is the blank model, n_i is the number of the total machining process, m_k is the total number of steps in the *i-th* process i, FC_{ij} is the feature cutter volume of the *j-th* step in the *i-th* process.

As in (1), the relationship of in-process model between the k-th process and the k–1(th) process is shown below:

$$\mathrm{Pro}Model_k = \begin{cases} \mathrm{Pro}Model_{k-1} - \sum_{j=1}^{m_k} FC_{kj} & (2 \le k \le n_i) \\ PartBlank & (k=1) \end{cases} \quad (2)$$

On the condition of blank model existing, the in-process model corresponding process k is generated through Boolean operation between the model of process k-1 and collection of feature cutter volumes instantiated by the current process. As you can see, the solving process corresponds with mechanical processing, it is a forward method evolving from the blank to the workpiece. As shown in Fig. 2, there are two steps in the process k: truning outer diameter (Δ_{k_1}) and drill hole (Δ_{k_2}), so the feature cutter volume collection can be expressed as follow.

$$\sum_{j=1}^{m_k} FC_{kj} = \Delta_{k1} + \Delta_{k2} \quad (3)$$

In-process models of next process are built with the method of Boolean Difference.

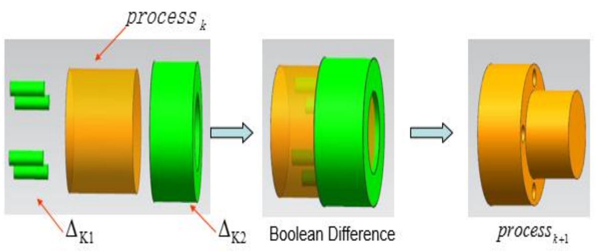

Figure 2. Feature cutter and in-process model

C. *Solution of Building the In-Process Model*

Boolean subtract is operated to minus the feature cutter from the linked in-process models. At the same time, since linkage has been established among in-process models with WAVE technology, the Boolean operations will automatically update in the subsequent in-process model. Automatic process modelling technology according to the above principle to simulate machining results, each working step removal feature cutter can be divided into the following five steps:

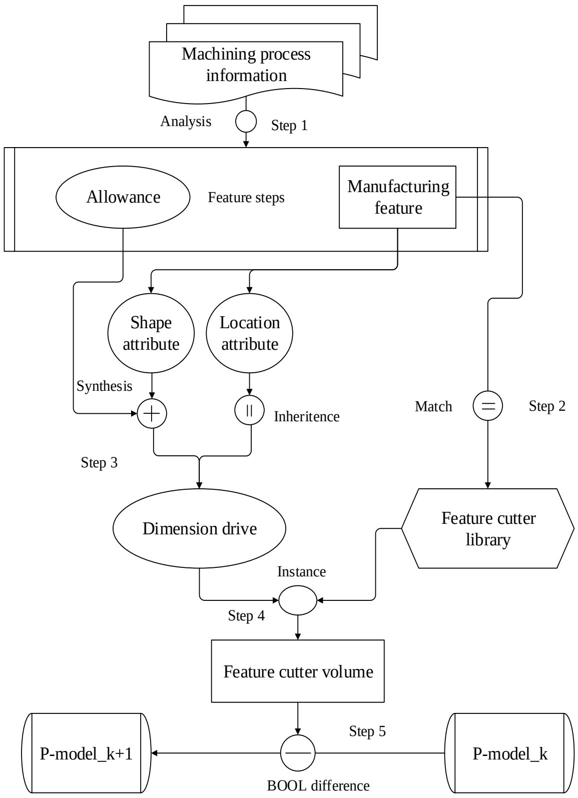

Figure 3. Automatic generation of in-process model

Step 1: To parse process route and content, getting information of manufacturing feature properties and machining allowance.

Step 2: To match the feature cutter volumes, depending on the type of manufacturing feature in the library of feature cutter volumes automatically matching the corresponding feature cutter.

Step 3: To calculation the size and position of feature cutter, depending manufacturing feature shape properties and machining allowance information to get drive size, according to positioning properties to place feature cutter.

Step 4: To instantiate feature cutter volumes, instantiating the volume with the dimension information getting from the Step 3.

Step 5: To subtract the feature volume from workpiece, placing the feature cutter volume at the position pointed in the step 3, then subtracting the instantiated feature cutter volume from the workpiece model to get the current in-process model.

The corresponding features will be added in every feature step by repeating the steps mentioned above. And the features in current step will be inherited by the child in-process model automatically because of the associative linkage.

IV. Automatic Annotation for In-Process Models Based on Model Defined (MBD)

Usually, standard design model not only includes the information about geometry, but also includes various kinds of dimensions and machining process constraints. These manufacturing process information are integrated into the model, which convenient the process designers control all aspects of product manufacture. However, the in-process models automatically generated can only express the specific structure of the workpiece, there is no integration of these processes information. As it shows in Fig. 4, the default of manufacturing information will impact the subsequent process analysis, product testing and other aspects of manufacturing and processing.

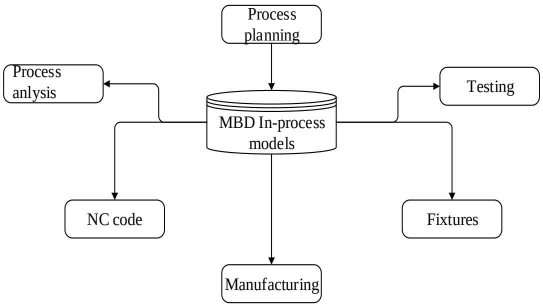

Figure 4. Data transfer mode base on MBD in-process models

Currently, the solution for dealing with such problems depends on the experience of process staffs. They manually marked the manufacturing information on the in-process models, which includes the dimensional tolerance, form tolerances, roughness and so on. What's more, a complex part has t dozens of processes and in-process models, which are to be marked with manufacturing dimensions by process staff. This method will greatly increase the workload reduce the efficiency of work. The automatic method for annotation based on recognized manufacturing features relies on international standards, which reduces the workload of process staffs and ensures the accuracy and standard of dimension.

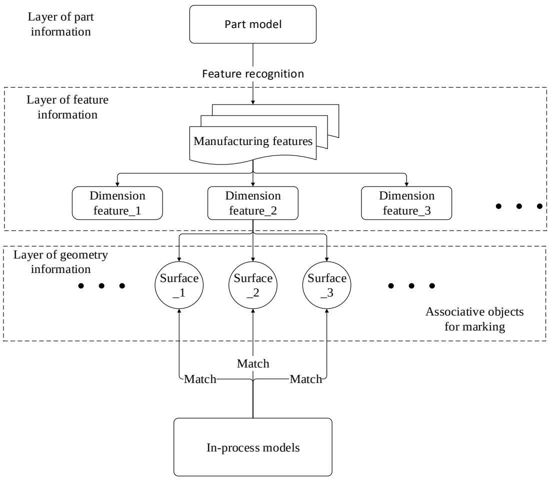

Figure 5. Data transfer mode base on MBD in-process models

A. Extraction for Annotation Information

As shown in Fig. 5, annotation information comes from three levels: the part layer, the feature layer and the layer of geometry such as B-Rep surfaces. The part layer contains the relationship between different features. Feature layer is the core information of the automatic annotation; Feature layer contains parent features (machining feature) and child features (annotation features), and the different features map the different structures and annotation style. Geometry layer is used to get the detailed basic data, and the associated objects of annotation.

Annotation of manufacturing features can be divided into two categories, one is the shape dimensions for the feature structure, which called amorphous dimensions; the other is dimension for the feature position on the part model or the relationship with other features, which called the position dimensions. A formula is used to demonstrate all dimensions for manufacturing features:

$$\mathrm{G} = \sum(Fs, L, T, V) + \sum\left(F_{(p)}, L, T, V\right) \qquad (4)$$

Explanation of the formula (4): the Fs represents reference object for posited annotation in features. The $\mathrm{F}_{(\mathrm{p})}$ is the collection of reference objects for shaped annotation of the features. The L is the location of the annotation. The T is style symbol of the annotation such as $\emptyset$, the symbol of diameter. The V is the value of the dimension.

B. Implication Steps for Automatic Annotation

Automatic annotation need to complete extracting the geometry objects, building the annotation rules for different features and setting the layout of the style for dimension. The detailed steps are listed in follows. And an automatic annotation example for in-process model is shown in the Fig. 6.

Step 1: To select the reference surfaces as the main and aid reference for posited dimension.

Step 2: To read the attribute of the recognized features.

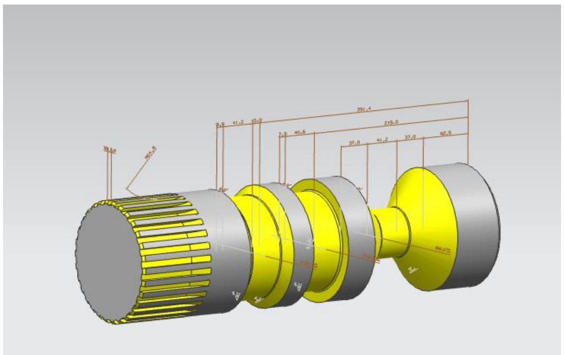

Figure 6. Automatic annotation for manufacturing features on In-process model

Step 3: To determine the type and the method of thedimension base on features attribute.

Step 4: To set the layout of the dimensions base on the annotation objects and the reference information.

V. Key Techniques in the Process Model Generation

The principle of the in-process model generation is cutting the feature volumes from the blank or in-process model continually, getting the in-process model corresponding to the model finally. There are two key techniques in the generation procedure:

(a) To instantiate custom features, creating features cutting body.

(b) To establish the relationship of correlation model, using WAVE technology to dynamic update manufacturing characteristics of models.

A. *To instantiate Feature Cutter Volume*

The effect of feature cutter volume is similarity with the tool in manufacturing working on the workpiece in cutting, having both the geometric constraints and space requirements.

$$FeatureCut = MID + Size + Location \tag{4}$$

The instantiation of feature cutter volume is depending on the type of manufacturing feature (MID), size and location constraints to quickly build a block with processing significance. For different manufacturing feature, specific methods of constructing are different, but the three elements as follows are same. Based on the different complexity feature cutter, there are four different building methods:

(a) Simple manufacturing feature, such as face, outer cylinder, simple hole, etc., can be directly parameter drive to establish feature cutter.

(b) The more complex features, but has certain modelling rules, such as slotting, relief groove, the ladder hole, etc., to create according to the CAD user defined feature (UDF).

(c) With complex cross section, irregular features, such as irregular groove, the method is to extract the sketch section, by operations such as tensile to instantiate the object.

(d) The complex surface characteristics, such as b-spline curved surface, the method is to copy the design surface, with synchronous modelling to create feature cutter.

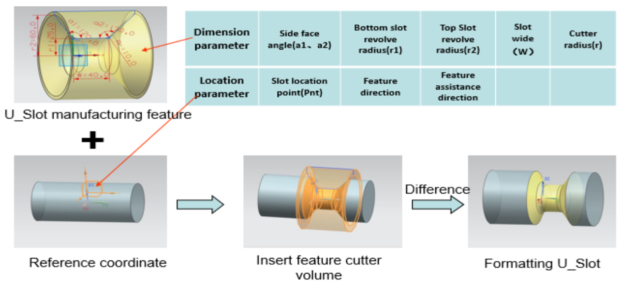

Figure 7. The instantiation of U-shaped groove feature

As shown in Fig. 7, it is an instantiate process of feature cutter volume for the U-shaped groove, which belongs to the complex but regular features. The U-shaped groove has the stable and regular geometrical structure. The feature cutter volume can be rapidly initiated by the UDF technology to build the in-process model.

B. *WAVE Technology of Correlation Process*

Using UG/WAVE technology to establish the incidence relation between in-process models, to make the follow-up in-process model can automatically inherit the early manufacturing feature. In the method of forward direction generation of in-process model, the common practice is constantly on the replication of last step in-process model, on the basis of the model adding manufacturing feature, getting this process corresponding in-process model. To establish incidence relation between the in-process models the biggest advantage is that can automatically update the manufacturing features. Practical application is likely to appear a new complex features or need to timely change process model, so the follow-up process model can automatically change, to improve the adaptability and flexibility of the system.

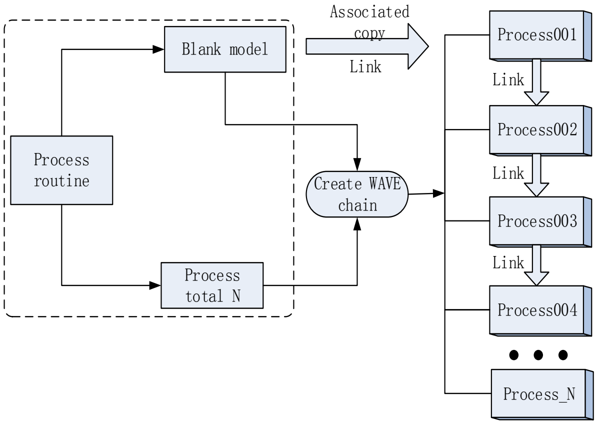

Figure 8. To establish associative relation between the In-process models

Fig. 8 shows that before adding manufacturing feature cutter volume, according to the total working procedure, N associative components are created in turn by WAVE Associative Linker. The blank model is added into the created components. Then the feature cutter volumes inserted into corresponding components to build the in-process models. The specific implementation code is as follows:

```
UF ASSEM_set_work part (assemprt ID);
    Add Assembly Component (temp_string, instance ID,
Occurrence ID);
    Get Current Component Body (occurrence ID, P_body
 Vector);
int j=0;
do
{Kmmpsug _ Close (partpath [j]);
    Create New Component (partpath [j], location, comp_
    Include _ obj _ vector, temp _id);
    UF_ASSEM_ask_occs_of_part (assemprtid,tem_id,
    &P_occ);
    UF_ASSEM_set_work_part (tem_id);
    UG_assem_wave_link_body (P_bodyVector);
    P_bodyVector.clear();
    GetCurrentComponentBody (*P_occ, P_bodyVector);
    UF_ASSEM_set_work_part (assemprtid);
    j++;
} while (j>0 && j<n_process);
```

The associative components can be created by the method mentioned above. The blank model is associative copied in the components, then inserted the corresponding feature cutter volumes according the process planning. Finally, the in-process models are formed through removing the feature cut volumes from the component parts by subtract Boolean operation. The changes of every child components come from the subtraction with the current feature cutter volumes and inheritation of the changes parent process.

VI. Instance of Process Model Generation

Based on the manufacture features and the key technology of building process model, this approach has been programmed on the VS2010platform and NX re-development interface technology(NXOPEN), successfully illustrates the feasibility of the in-process model forward generation in the 3D CAPP system (KMCAPP-M).

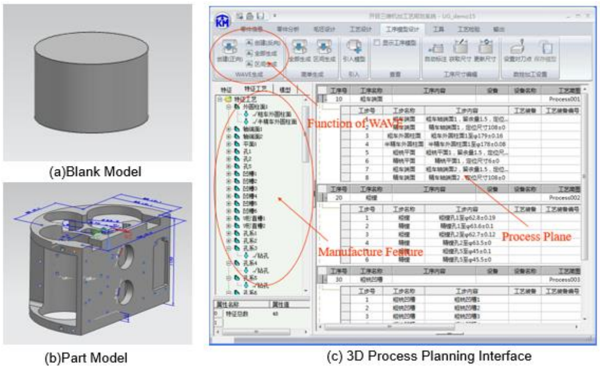

Figure 9. The design model and the process planning content

The paper takes a process of a typical part as an example to show the result of method discussed. Fig. 9(a) shows the blank of the part. Fig. 9(b) shows the design model of the part. Fig. 9(c) shows interface of the part's manufacture process route. The in-process models are generated according to the given process routes through the method mentioned above. Fig. 10 shows the in-process models of the five machining process.

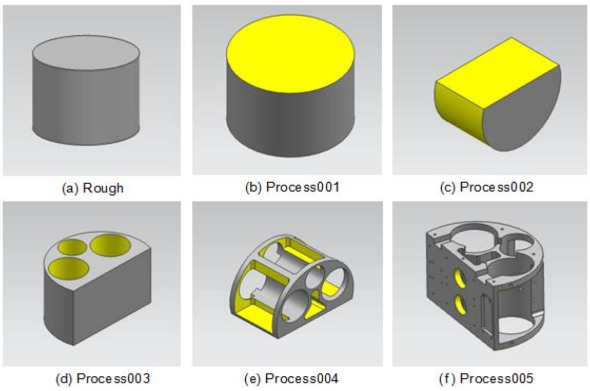

Figure 10. Process model generated by planning model

In practical engineering applications, we may have to adjust the size or shape of blank, or get some problems with unconventional manufacturing characteristics, such as some free-form surface, then we hope to complete the design of in-process model by means of manually adding manufacturing characteristics. However, the Manual method wastes time and increases the cost of process. It is contrary to the purpose of the system design. The process model generation method supporting WAVE technology can realize the function of automatically updating process model. After one process finished inserting new manufacturing features, the subsequent step model will be automatically inserted with the new manufacturing characteristics. Thais obviously improves the efficiency of the process model generation. As shown in Fig. 11, the blank is added two different groove features, then the in-process models of the sequent process automatic update with the new groove features.

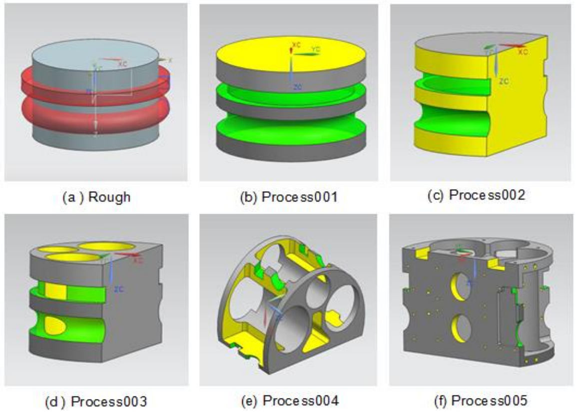

Figure 11. The process model updated after blank's modifying

VII. Summary

This paper demonstrates a new method for in- process model generation, building associative relationships between the process models by means of WAVE technology, instantiating the manufacturing features cutter volume and matching for the machining process according to the process information .As result, in-process models are formatted according to the process route automatically. To verify those methods, automatic in-process model generation is demonstrated by a typical part. Some of the advantages of the proposed approach are listed below:

1) The process data information based on manufacturing features cutter volume ensures the accuracy of in-process model in revolution.
2) The usage of UG_WAVE technology, when a new feature appears or the design models need to resize in the actual project, can automatically update the related in-process models. This improve efficiency and flexibility of work.

Process model generation method described in this paper was verified successfully on KM3DCAPP-M system, a commercial CAPP system. The method of this study appropriate for the part with plenty manufacturing features both in research scope and engineering applications. But it still needs to be further improved in the aspects shown as follow:

1) The in-process models currently produced has not been marked complete dimension and manufacturing information.
2) The manufacturing features can be automatic updated from parent process. However, the updated features will be lost if the order of planning process is changed.

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