

Associating a Design Model and its Machining Process Plan

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ABSTRACT

One of the major problems with the conventional process of creating products is the poor association between product design and manufacturing engineering. Although, a product is represented as a 3D CAD model, in-process models (IPMs) of a process plan are usually 2D drawings that have little association with the product model. The lack of association requires an excessive amount of effort for managing changes. The concept of digital product creation has been proposed to integrate all the activities involved in the process of creating products. This paper proposes a methodology based on digital manufacturing technology that keeps a proper association between a product model and its machining process plan. For the associativity, the method generates IPMs by removing machining volumes from the stock model (rough part). This paper classifies machining process planning into two different stages: initial process planning and detailed process planning. The first stage focuses on developing a reasonable initial process plan, while the second stage can be viewed as verifying a detailed process plan with various downstream applications. Since the two stages have different requirements for IPM generation, this paper proposes two different methods of IPM generation.

Keywords: Process planning, in-process model generation, IPM, cutter swept volume.

1. INTRODUCTION

If manufacturers are to remain competitive in the ever-changing market place, they must strive to improve not only their products, but also their process of creating products. In industries with high volume production, the product creation process, as shown in figure 1, usually involves the product, process and resource domains [1]. The product domain covers the design of individual parts, which can be divided into three categories: concept design, finished part design and rough part design. The process domain covers detailed planning of the manufacturing process including machining, assembly and inspection. The activities of the resource domain include machine tool design, fixture design, gage design and plant layout and simulation. In this article, the term process planning refers to the planning of the machining process of prismatic parts.

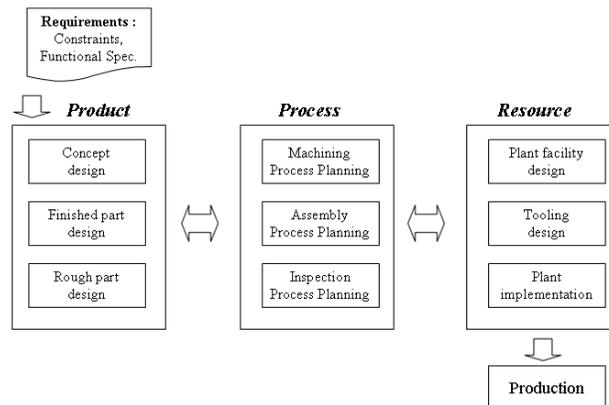


Fig. 1. Product creation process

Although, the overall procedure of creating products is almost the same for different manufacturers, efficiency may vary according to the information management technology which drives the product creation process. Figure 2 shows a conventional system of information management for the creation of products. Although, using 3D CAD systems for product modeling is very common, 2D drawings are still essential for the communication in the manufacturing engineering world. Normally, process engineers make 2D drawings, but the association between the drawings and the product model is weak. Although, some software systems partially assist engineers in making the 2D drawing, the task is still labor intensive.

One of the major problems, arising from the lack of association, is the difficulty of managing change: changes occur frequently in the process of crating products and managing change is a labor intensive job. The description of a manufacturing process of a product could require thousands of 2D drawings; reflecting a major design change in all those drawings would be laborious for process engineers. Thus, maintaining a suitable association between the various data objects involved in the product creation process is a crucial problem that has brought about the concept of digital product creation. The ultimate goal of digital product creation is to design the product and manufacturing process with full visualization and simulation in an integrated manner [1, 2, 6].

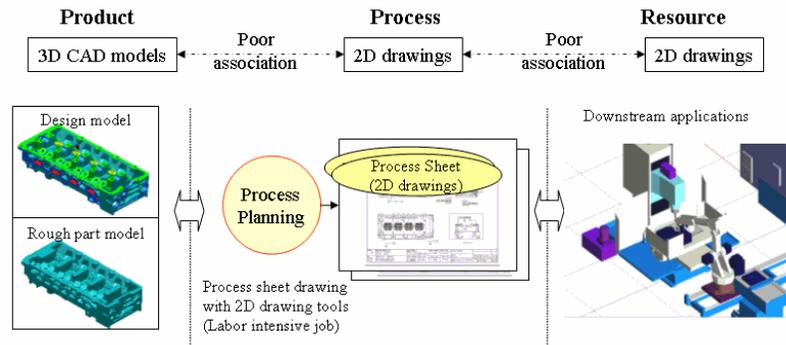


Fig. 2. Conventional information management in the product creation process

To integrate the product creation process, we need to focus on the process planning which plays a key role in the process of creating products, as shown in figure 3. Once a process plan is made, it becomes the common starting point for various downstream applications. Process planning involves determining the necessary manufacturing processes and their sequence in order to produce a given part economically and competitively. To accomplish this task, we need to generate the appropriate machining information from a model developed by product designers. Whenever something changes in the process plan, we need to determine which downstream applications will be affected. A process plan can be considered as a sequence of in-process models (IPMs) that occur in between process steps during manufacturing. Maintaining a correct set of IPMs, which is the main input of many downstream applications, is very important. For example, the machine tool builders use IPMs for designing the machining system, and the operators use them for gauging. The current industry practice of making 2D drawings to represent IPMs is a time consuming job. A more serious problem is the difficulty of managing the changes that comes from poor association between 3D design model and manually created 2D IPMs.

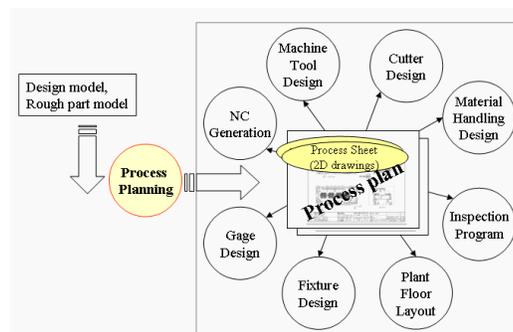


Fig. 3. Process planning in the product creation process

To support the concept of digital product creation, it is necessary to develop an automatic method of generating IPMs, so that any changes in the design model can instantly be easily propagated to downstream applications. Conceptually, IPMs should be generated from a process plan by removing machining volumes from the rough part model, as shown in figure 4. We can use 3D solid models for IPMs and, if necessary, extract 2D drawings from the solid models. Few research results have been published on the automatic generation of IPMs. Ramesh et. al. [7] proposed a system to automatically generate IPMs for automotive powertrain components. They classified the machining features into two categories: template features and non-template features. The machining volumes for template features are created by instantiation, and the machining volumes for non-template features are created by selectively offsetting and extruding the face boundary on the final part model.

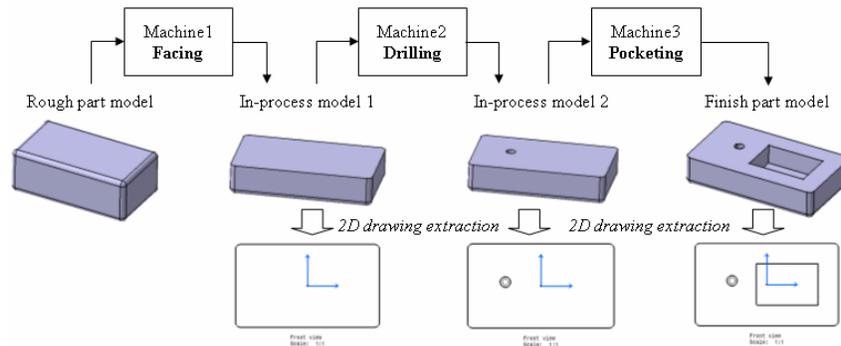


Fig. 4. In-Process model generation

For the integration of product creation process, this paper proposes a framework of process planning based on the concept of digital manufacturing that aims at full visualization and simulation of manufacturing plans. We classify a process planning activity into two different stages: initial process planning and detailed process planning. The initial stage focuses on developing a reasonable process plan, while the detailed stage verifies or simulates a process plan rather than developing a new plan. Because both stages have different IPM requirements, we propose two different methods of IPM generation: one for initial IPMs and the other for detailed IPMs. Both methods are highly optimized by using the inherent characteristics of prismatic machining.

The rest of this paper is organized as follows: Section 2 reviews the approach of this paper to integrated process planning; Section 3 addresses the IPM generation method for the initial stage of process planning, and Section 4 addresses the IPM generation method for the detailed stage of process planning; finally, a summary is given in Section 5.

2. APPROACH TO INTEGRATED PROCESS PLANNING

In the process of creating products, process planning is not a single-time activity. The early stage of process planning produces an initial process plan, and the initial process plan becomes the starting point for various downstream applications, as shown in figure 3. Later, however, newly generated information from downstream applications returns to refine the process plan. For prismatic machining, there are four types of machining operations: facing, pocketing, axial and curve-following. Except for the axial and curve-following machining operations, most of machining operations for prismatic machining use a cylinder-shaped cutter called a flat end mill. For axial and curve-following machining operations, the use of special shaped cutters that fit the machining feature is possible; for example, a dovetail mill, an I-shaped mill and a double mill.

Figure 5 shows two different schemes for IPM generation, one is for the initial process planning and the other is for the detailed process planning. In the initial stage of process planning, we define a sequence of machining operations by specifying the type of machining operation, the target geometric elements and the cutter specification. Since the cutter path (NC code) is not available at this stage, we can not compute the actual compute cutter swept volume (CSV) of a machining operation. Consequently, we have to estimate the machining volumes in a reasonable way to generate the initial IPMs that should be the starting point for downstream applications, including the cutter path generation. We call the estimated or intended machining volume a 'target machining volume' (TMV). Once the TMVs are computed, it is possible to compute the IPMs by removing the TMVs from the rough part model, as shown in figure 5-(a). The initial

IPMs could then be used for various downstream applications, including machine tool design, NC generation and fixture design. As a result, we obtain more information on such things as the NC cutter path, the cutting conditions and the fixture design. This newly generated information needs to be used to refine the initial IPMs, and we are then able to start the detailed process planning for the full verification of the process plan. At the stage of the detailed process planning, the important factor is the accuracy of the IPMs, because using inaccurate IPMs to verify the results of process planning may cause costly mistakes. We generate accurate IPMs by removing the CSVs from the rough part model, and compute the CSVs from the cutter path and cutter geometry, as shown in figure 5-(b). The IPMs generated from the CSVs could be different from those generated from the TMVs in the initial process planning stage in which the actual cutter paths are not considered.

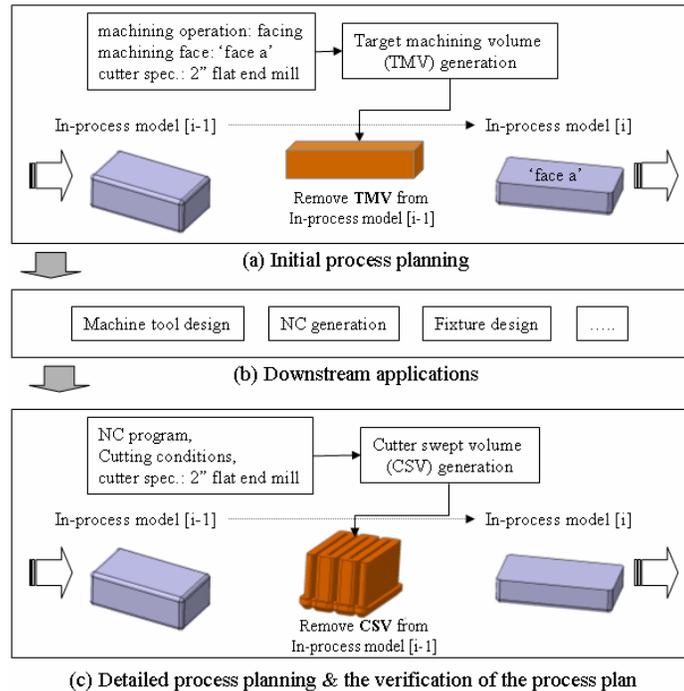


Fig. 5. Target machining volume (TMV) and cutter swept volume (CSV)

It is possible to evaluate the feasibility and validity of machining operations by considering CSVs. If a CSV interferes with a product model or fixtures that should not be machined, we call this interference a gouge (or over-cut) error. In this case, various solutions exist. For example, we could change any of the following things to remove the gouge error: the sequence of machining operations, the cutter path, the cutter, the machining operation, the fixture design or the machine tools. We would then need to propagate the change to related areas and reevaluate the process plan.

3. TARGET MACHINING VOLUME

As discussed in the previous section, TMV computation is necessary for generating IPMs at the initial stage of process planning. Since the cutter path is not available at this stage, we need to generate TMVs in a reasonable way by using the available information, such as the type of machining operation, the cutter type, the machining target geometry and the casting tolerance. However, in the case of axial and curve-following machining operations, extracting the cutter path from the target geometry is intuitive, especially for such features as holes and guiding curves where the target geometry restricts the cutter path. For these types of machining operations, we can compute the actual machining volume (CSV) instead of estimating the machining volume (TMV). Thus, for TMV computation we focus only on the facing and pocketing machining operations.

One of the intuitive methods for TMV computation is to extrude the machining target face. Figure 6-(a) shows a target machining face and its outer boundary, while figure 6-(b) shows that extruding a planar face to define a volume. However, the generated volume may not be satisfactory because it does not consider the attributes of a rough part model. Usually, a rough part model is made by casting, which involves the casting tolerance. If the TMV does not

consider the casting tolerance, excessive material may be left on the stock. The error could be crucial because the excessive material may lead to incorrect IPMs affecting many downstream applications. One possible solution is to expand the outer boundary of the face by applying 2D offsetting [5, 8] to it with the casting tolerance. We can then extrude the expanded boundary to compute the TMV.

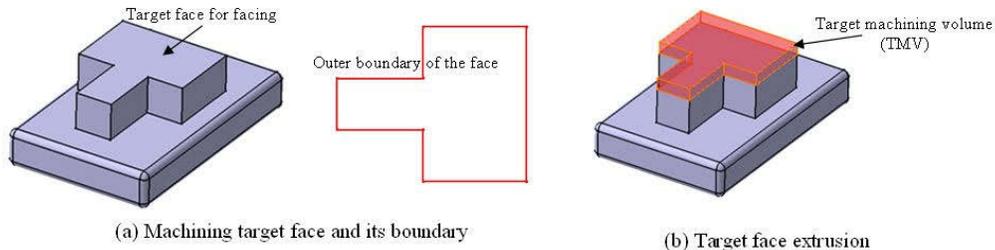


Fig. 6. TMV by extruding the machining target face

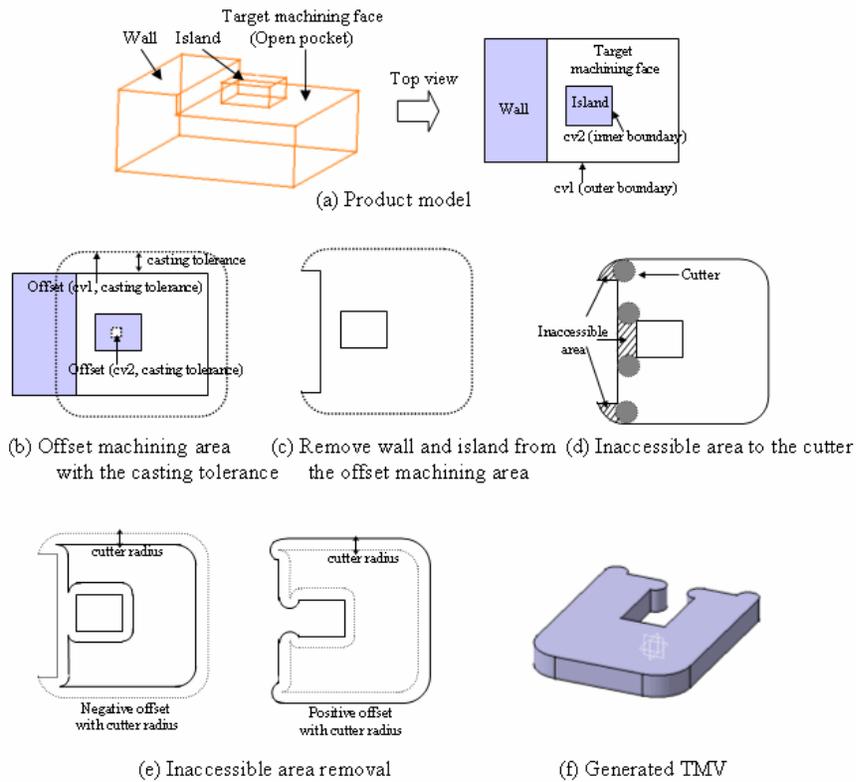


Fig. 7. TMV for an open pocket

At the initial stage of process planning, the cutter specification might be given or not. Once a cutter is defined for a machining operation, considering the cutter information for the generation of the TMV is desirable. Figure 7 shows an example of an open pocket. The target machining face, shown in figure 7-(a), is adjacent to a wall and includes an island. As depicted earlier, we have to consider the casting tolerance by expanding the machining area which is bounded by two curves (cv1 and cv2). To expand the machining area, we offset the machining area with the casting tolerance [5, 8]. As a result, figure 7-(b) shows an expanded area bounded by the two offset curves, which are denoted by dotted lines. In this case, the expanded machining area interferes with the wall and island areas, which indicates the unfeasibility of the machining operation. To avoid the interference problem, we have to subtract the wall and island areas from the expanded machining area, as shown in figure 7-(c). At this point, we also have to consider the cutter

specification, if it is available. Figure 7-(d) shows a cutter and areas inaccessible to the cutter. Consequently, we have to subtract those inaccessible areas from the expanded machining area, which can be easily done by applying two offset operations to the expanded machining area, as shown in figure 7-(e): firstly, by using a negative offset operation with the tool radius, and secondly by using a positive offset operation with the tool radius. Figure 7-(f) shows the TMV generated by extruding the machining area while considering the following three factors: the casting tolerance, the wall and island interference, and the cutter specification. Depending on the attributes of the specific domain, we have to choose which factors needed to be considered at the initial stage of process planning stage. The bottom line is to generate proper IPMs for downstream applications.

Although the proposed TMV computation method seems to be automatic except for picking the target machining geometry, cases requiring more manual work may exist. Figure 8-(a) shows a simple example involving two machining operations: facing and pocketing. The facing operation can be defined by picking the target face from the design model, shown in figure 8-(b1). But the face ('Face 1') can not produce a proper IPM for the facing operation, because it has been changed by other design steps. In this case, it is necessary to define the machining area by manually modifying the boundary of the face, otherwise an incorrect IPM will be produced, as shown in figure 8-(b3).

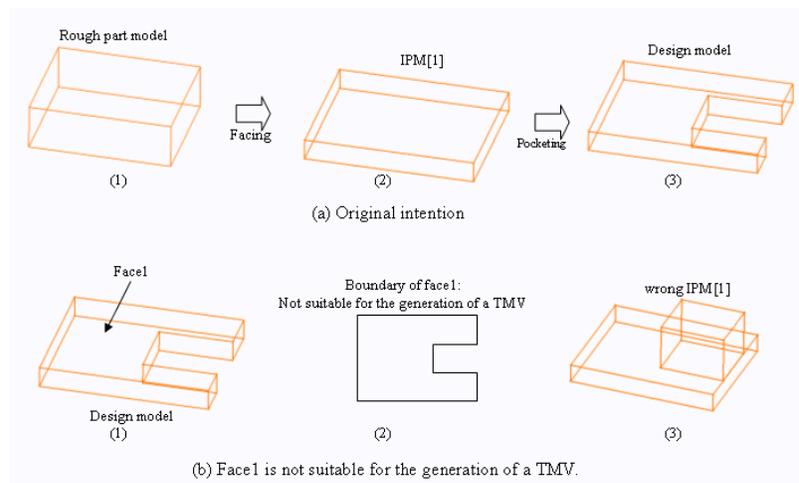


Fig. 8. Difficulties of automatic TMV generation

4. CUTTER SWEEPED VOLUME

Initial IPMs provide input to downstream applications, such as cutter path generation, fixture design and machine tool design. As depicted earlier, the results from these downstream applications should be recycled to refine the initial process plan. At this time, the important factor is the accuracy of IPMs because inaccurate IPMs may lead to costly mistakes. Since cutter paths become available by this stage, we can compute the actual machining volume.

One intuitive idea is to use a cutting simulation technique for the creation of IPMs. Since cutting simulation is recognized as a standard means for checking or verifying cutter paths, a considerable amount of attention has been paid to the issues of cutting simulation [9, 14]. Generally, cutting simulation shows the machining process by visualizing the work piece after each NC command. Using a complete solid representation for the visualization at each NC command is computationally intensive. Although cutting simulation may be used for IPM generation, it is not economical in terms of computational cost.

The approach of this paper is to generate IPMs by removing CSVs from the rough part model. The difficulty of this approach is in the computation of the CSV. There have been many research results [10-13, 15] for the general sweep operation of a 3D solid. Computing useful representations (B-rep) of swept volumes is widely viewed as difficult and expensive. In particular, the trimming problem of a swept volume [10] has been known to be one of the biggest obstacles. The trimming problem arises from the necessity of characterizing self-intersections of the swept volume boundary that occur for many sweeps, and the trimming problem is one of the most difficult aspects of any process for analyzing and representing swept volumes. Intuitively, we can consider the trimming problem as a surface-to-surface intersection problem and attack it using any of the known surface-to-surface techniques. However, this approach might not take advantage of the inherent sweep structure that generates the self-intersections of the swept volume. Some

analytical techniques have been devised for reducing the expense associated with the trimming problem. Blackmore *et al.* developed a method called a sweep-envelop differential equation method (SEDE) for computing swept volumes for smooth objects undergoing arbitrary smooth motions [10, 13]. Schroeder *et al.* used implicit functions to obtain swept volumes [15]. Some researchers employed ray-casting methods for obtaining a swept volume [11]. These methods are relatively robust and they intrinsically avoid the trimming problem, but they require a significant increase in computational cost. Though much work has been done in search of an effective solution for the trimming problem of a general swept volume, a completely satisfactory solution still remains elusive.

Some of the earlier results may be used for computing the CSV of a machining operation but these approaches might not take advantage of the inherent characteristics of the prismatic shape machining. In prismatic shape machining, the cutter moves on a plane, which means that it might be possible to compute the CSV by using 2D geometric algorithms instead of using generalized 3D algorithms.

For facing and pocketing machining operations, a flat end mill, which can be considered as a combination of cylinders, is normally used. To obtain the CSV, we can compute the swept volume of each cylinder separately, and add them. The swept volume of a cylinder can be computed by using 2D curve offsetting [5, 8], as shown in figure 9. We consider the cutter path (figure 9-(a)) as a closed curve with zero area, and offset it by the cylinder radius (figure 9-(b),(c)). The swept volume of a cylinder can be obtained by extruding the offset curve (figure 9-(d)). If the NC file consists of multiple cutter paths, one more step is required. After obtaining the offset curve of each cutter paths, we have to compute the merged area of the offset curves before the extrusion. The area merging operation includes another well-defined 2D geometric problem, a polygonal chain intersection problem [4]. Hence, we split the CSV computation of the flat end mill into two 2D geometric problems: 2D curve offsetting [5, 8] and 2D polygonal chain intersection [4]. Both problems have been paid a considerable amount of attention by many researchers, and highly optimized solutions exist.

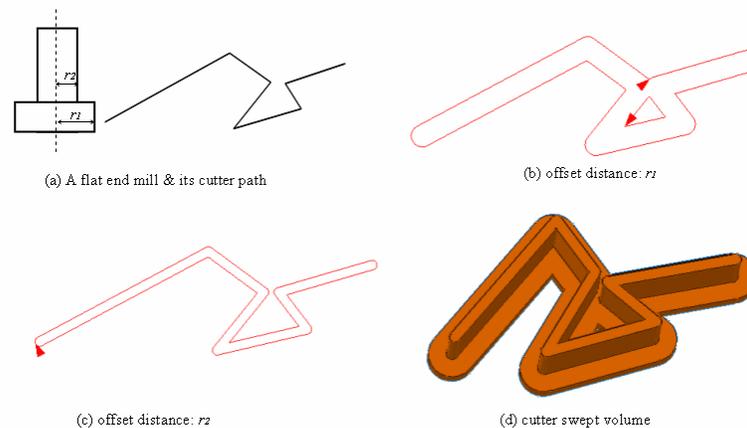


Fig. 9. CSV of a flat end mill

For the case of a general shaped cutter that is not a flat end mill, we use a recently proposed algorithm called a polygonal extrusion algorithm [3]. The polygonal extrusion assumes that a 2D cross-sectional polygon (sweeping polygon) moves in space while its containing plane is kept orthogonal to the tangent direction of the trajectory, which is a planar curve that has no self-intersection. Because we are able to describe a cutter with its 2D cross-sectional polygon, the use of the polygonal extrusion algorithm for the CSV is possible as long as the cutter path exists on the plane.

The polygonal extrusion algorithm is based on a proven 2D geometric technique, called a Voronoi diagram. It is possible to construct the Voronoi diagram of a cutter path with $O(n \cdot \log n)$ time complexity, where n is the number of line segments on the cutter path. As shown in figure 10, the Voronoi diagram of a cutter path consists of Voronoi edges and vertices. Once constructed, the diagram makes the task of computing the machining volume easy because the Voronoi edges and vertices correspond to the edges and vertices of the CSV. Details can be found in [3]. This method can be expanded for machining operations that contain multiple cutter paths since computing the Voronoi diagram of multiple polygonal chains is also possible, as shown in figure 10-(b). The major advantage of this method is that the

swept volume does not have any self-intersections or trimming problem because all possible self-intersections are automatically removed by the attributes of the Voronoi diagram. This is a big advantage over conventional sweeping algorithms suffering from the trimming problem. Figure 11 shows some examples of CSVs, and we can compute the IPMs by subtracting the swept volumes from the workpiece.

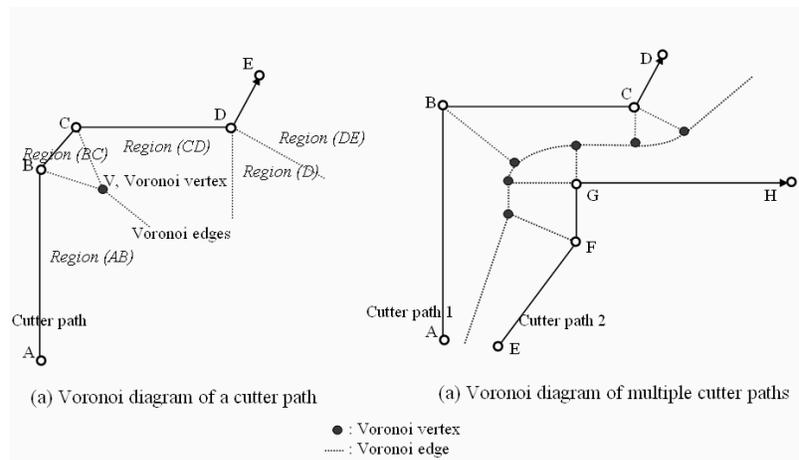


Fig. 10. Voronoi diagrams of cutter paths

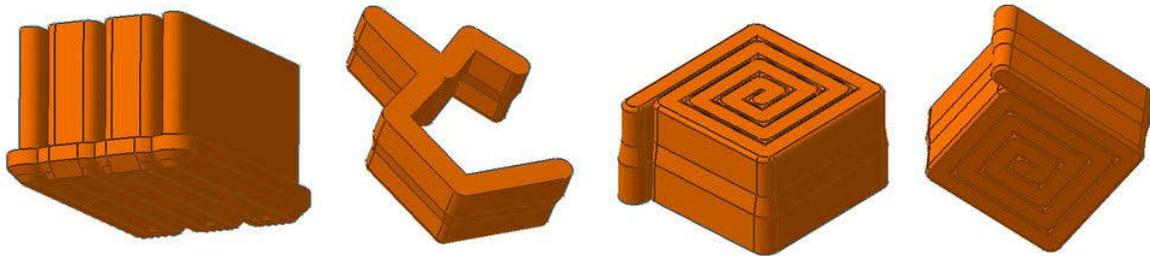


Fig. 11. CSV examples

5. SUMMARY

The ultimate goal of digital product creation is to design a product and manufacturing process with full visualization and simulation in an integrated manner. To successfully integrate the process of creating products, we need to maintain a proper association between various data objects that belong to the product, process and resource domains. Ideally, a change in any domain should be propagated automatically to related applications. One of the biggest obstacles to integrated change management is the informational gap between the product design and process planning. Conventionally, process engineers manually describe IPMs with 2D drawings that have a very poor association with other objects. Manual IPM creation is undesirable, because manually created IPMs cannot be automatically updated as something changes in the process plan or in the product model. In addition, the laborious task of creating IPMs manually could cause costly mistakes because of potential human error.

To cope with this problem, it is necessary to generate IPMs automatically from the process plan and the product model. An IPM should be represented as a 3D solid model and computed by removing the machining volume from the rough part model. Roughly, process planning comprises two stages: initial process planning and detailed process planning. Initial process planning focuses on developing a reasonable process plan, while the detailed process planning can be viewed as verifying the process plan rather than developing a new plan. Because the two stages have different requirements for IPM generation, we develop two different methods of IPM generation. The initial stage of process planning generates IPMs by removing TMVs from the rough part model. Three important factors have been identified for TMV generation: casting tolerance, wall and island interference and cutter specification. We have to choose which factors to consider depending on the attributes of each application domain. In detailed process planning, the accuracy

of IPM generation is important, because inaccurate IPMs may affect the verification results of the process plan. Since cutter paths are available in the detailed stage of process planning, we compute IPMs by removing the actual CSVs from the rough part model. For the CSV computation, this paper employs an algorithm called a polygonal extrusion algorithm [4] which is originally developed for CSG modeling. The CSV computation procedure is very efficient because it uses inherent characteristics of prismatic machining and uses highly optimized 2D geometric algorithms instead of generalized 3D algorithms.

Although the focus of this paper is on the machining process planning, various other issues in process planning exist such as assembly process planning and inspection process planning. To maximize the benefits of digital manufacturing technology, we need to achieve an intelligent balance of all areas involved in the product creation process. Without such balancing, the less advanced areas will continue to hamper and in some cases, nullify the efficiency of the more advanced areas.

6. REFERENCES

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