



## Geometric Modeling, Design and Analysis of Custom-Engineered Milling Cutters

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### ABSTRACT

The geometric modeling of the cutting tools is an important aspect for the design and manufacturing engineers from the viewpoint of shape realization. The geometry of cutting tools' surfaces based on two-dimensional (2D) projected geometry approach has certain limitations. This definition is also inadequate due to inaccuracy and non-applicability of the model for further manipulation. To address these issues, an accurate three-dimensional (3D) surface-based generic definition for a few families of custom-engineered milling cutters has been developed. The proposed geometric definition of the customized cutter is developed in terms of biparametric surface patches using proposed 3D rotational angles rather than the conventional 2D angles. The non-uniform rational B-spline (NURBS) curve(s) and generation of sweep surfaces based on it are utilized for the shape generation of cutting elements of the generic cutters. This representation scheme enables tooth shapes to be controlled by manipulating control polygons and sweep trajectories and in the process varied tool geometries can be generated. Further, an interface is developed that converts the proposed 3D parametric definition of the cutter into an intermediate neutral CAD format. This helps in rendering the cutter model in any CAD modeling environment.

**Keywords:** Milling cutters, Cutting tools

### 1. INTRODUCTION

The fabrication of free form sculptured surfaces such as those for airfoils, turbine blades, automotive components, shoe soles, etc. requires a significant effort toward the design and manufacturing of the custom-engineered (special) cutting tools correctly.

Development of accurate geometric models of special cutting tools holds a key position to create these surfaces. Traditionally, the geometry of cutting tools, including customized cutters, has been defined using the principles of two-dimensional projected geometry. Such definitions are two-dimensional (2D) in nature and 2D modeling is insufficient to support current analysis, prototyping and manufacturing technologies as they lack "information completeness". The growth of curve and surface modeling in the realm of Computer Aided Geometric Design (CAGD) helps a designer to accurately model the complex geometry of customized cutting tool surfaces.

#### 1.1 Problem Definition

This work makes an attempt to develop a novel unified representation scheme that can provide direct 3D generic definitions of custom-engineered (special) cutting tools for (a) their correct design and fabrication and (b) downstream technological applications. In view of the importance of developing special cutting tools to generate free form complex surfaces and mass manufacturing, we formally state the problems undertaken in this work as follows:

- (i) The geometry of a generic custom engineered cutting tool is to be defined using geometric modeling approach to develop its three dimensional model. 3D nomenclature that includes 3D rotational angles and other dimensional parameters is to be specified for the geometry of cutting tools.
- (ii) A cutter design interface is to be developed which may help render the generic definition of

custom-engineered cutting tools directly in any CAD modeling environment to validate the methodology and provide convenience in downstream technological applications.

(iii) The generic CAD model of custom-engineered cutting tools acts as a core model and the family (a variety) of special cutting tools may be generated by suitable modifications in the parameters of generic cutters. Besides, a few special cutters need to be developed and their geometry is optimized as per the specific application

## 1.2 Manufacturing Processes and its Classification

Manufacturing can be simply defined as value addition processes by which raw materials of low utility and value are converted into high utility and valued products. The process of manufacturing imparts some functional ability with definite dimensions, forms and finish to raw materials of inadequate material properties and poor or irregular size, shape and finish. The core of manufacturing operations is the process responsible for transforming the shape, size and finish of the object. Manufacturing processes can be broadly classified in three major groups, namely, (i) subtractive machining (removal processes), where material is removed from the blank due to relative movement of a cutting tool over a workpiece; (ii) additive manufacturing, that deposits material in an empty volume or layer so as to yield the desired complex configuration and (iii) shaping or forming processes that deform plastically a given volume or sheet of material.

### 1.3 Metal Cutting

Basically, machining is a semi-finishing or finishing process where the excess material is removed from the preformed blanks in the form of chips so as to impart required or stipulated dimensional and form accuracy as well as surface finish. It is perhaps the most versatile manufacturing process. Besides, it provides a higher degree of geometric complexity to the work. The cutting tool is one of the important elements in realizing the full potential out of any machining operation. It is the relative movement of the cutting tool(s) with respect to the work surface(s) that produces the machined surface. The material to be removed is pressed against the hard edge(s) of the cutting tool and made to flow. The material is removed due to shear deformation over the face of tool.

A cutting tool consists of two groups of functional parts. The first group consists of edges and surfaces responsible for actual cutting operation. These are critical elements of a cutting tool and form cutting element(s) or teeth of the cutter. The second group consists of shank, hub, disk, cylinder etc. on which the cutting elements are established. The elements of this group form cutter body and are non-critical as they are meant to complete the geometry. The geometry of a cutting tool consists of face(s) or rake surface(s), flanks, land, cutting edges and the corner(s) or nose. Face is the surface of the cutting tool along which the chip flows out, while flanks are the surfaces facing the workpiece.

### 1.4 Milling

Milling is a subtractive shape realization process that removes a predetermined amount of material from the work piece with the cutting tool rotating at a comparatively high speed. The cutting tool used for the purpose has multiple cutting teeth. The characteristic feature of the milling process is that each milling cutter tooth removes its share of the stock in the form of small individual chips during each revolution from the advancing work. A wide variety of operations can be performed during milling since both the workpiece and the cutter can be moved relative to one another independently or in combination. Milling consists of two motions: rotation of the cutter about its axis which is primary cutting motion, and a feed motion. In some applications, the feed is given to the workpiece while in other the workpiece is held stationary and the cutter is traversed across at a given feed rate. The feed motion is along a straight line in milling flat and cylindrical surfaces; it is rotary in milling surfaces of revolution and helical in milling helicoidal surfaces. Milling operations are performed on different machines with different type of cutters. Milling cutters are bodies of revolution, rotating about their axes, with equally spaced cutting teeth on their surfaces.

### 1.5 Drilling

The operation where the tool is rotated and fed along its axis of rotation while the work piece remains stationary is called drilling. The most common type of drilling is the operation with a twist drill to generate a hole. A twist drill with a shank has two (or more) cutting edges, each responsible for removal of work material. The tool used for drilling is the drill bit. The drill bit is a multipoint, end cutting tool. It cuts by

applying pressure and rotation to the work piece, which forms chips at the cutting edge. There are a variety of drill styles that each serves a different purpose.

## 2. Custom-Engineered Cutting Tools

A customized form tool is a cutting tool having one or more cutting edges with a defined profile or contour that will be reproduced as the desired form on the work surface. Basically, the geometry of cutting elements / edges (points) of form tools can be of single point or multipoint design. Besides, form tools may be classified according to type of cross-section, which may be (a) flat form tools, (b) circular tools and (c) end-form tools. Flat or block tools are further classified according to setting of the tool with respect to work piece like radial-fed or tangential-fed type. Further form tools are also classified with respect to orientation of tool axis in relation to work piece axis.

### 2.1 Need of Geometric Modeling for the Design of Custom- Engineered Cutting Tools

Geometric modeling is defined as generation of computer-compatible mathematical definition of geometry / shape of an object. In geometric modeling, we define a shape by a set of mathematical statements and logical relations satisfying a set of axioms. These axioms we interpret as true statements about the model, and the consequent general properties of the model we analyze and evaluate as representative of the modeled object itself. Geometric modeling is the process of creating these statements and relationships. Besides, geometric modeling is the construction or use of geometric models. Geometric models can be built for objects of any dimension in any geometric space. Basically, 2D, 2½D and 3D geometric models are extensively used in computer graphics. 2D models are important in computer typography and technical drawing. 2½D and 3D models are central to computer-aided design and manufacturing, and many applied technical fields such as geology, medical image processing, etc.

Computer-aided geometric design (curve and surface modeling) (CAGD) and solid modeling are the branches of geometric modeling. Computer-aided geometric design (CAGD) applies the mathematics of curves and surfaces to modeling, primarily using the parametric equations of differential geometry. Solid modeling allows us to combine simple shapes to create complex solid models. Solid modeling has its mathematical foundations in topology, algebraic geometry and Boolean algebra. Geometric modeling

has applications in the fields of computer animation, computer graphics, computer vision, robotics, CAD/CAM, fluid dynamics, and structural analysis.

## 3. Review of Literature

Abrari and Elbestawi, Zheng et al. have done a systematic study on cutting force modeling methods in peripheral end milling in the presence of cutter runout. The analytical representation of helical flute geometry is proposed by Lee and Altintas, Gradisek et al. Yucesan and Altintas, while cutting force prediction model is combined with models for cutter deflection and machining accuracy to study surface errors for end milling.

Chen et al. has presented manufacturing models to produce concave cone end milling cutters. Work on cutters other than end mills include geometric modeling of single point cutting tools by Rajpathak, design of cutters to manufacture helicoidal surfaces by Karunakaran and Dhande, design of hob cutters for generating the multi-cutting angles (radial rake angle, relief angle, and clearance angle) of helical cutting tools is proposed and design and manufacturing of hob for machining of precision involute gear.

Imani and Elbestawi have developed precise B-rep model of the cutter swept volume to update part being machined for each NC block, evaluate instantaneous chip geometry and model feed marks and scallops on the machined surface. 5-axis sculptured surface machining is simulated using discrete geometric models of the tool and work piece to determine the tool contact area and a discrete mechanistic model to estimate the cutting forces is presented by Fussell et al.

Optimizing the design of the milling cutter based on finite element based engineering analysis is done by Jha and Hornik also; simulation of metal cutting process using finite element method has been studied by Shet and Deng. To improve the accuracy of the model of milling operations, three-dimensional finite element modeling is performed by Pittala and Monno for the insert based face milling and ball nose end milling.

## 4. Objectives and Scope of the Present Work

The primary goals of this work are

(a) To develop three-dimensional definitions of the existing custom-engineered cutting tools (form, milling, special purpose, etc.) for machining free form

/ special surfaces as well as for mass manufacturing, and to define in detail its geometric modeling and

(b) To design and manufacture new custom-engineered cutting tools for some special applications (where the surface profile to be generated is already known).

Besides, we would also like to

- i. Develop surface based geometric models of custom-engineered cutting tools in terms of their surface patches using the evolved 3D rotational angles and other dimensional parameters.
- ii. Establish a set of 3D nomenclature for specifying the geometry of the special cutting tools.
- iii. Interface properly the new generic definition of custom-engineered cutting tools with advanced modeling software for customized applications.
- iv. Verify the surface model based definition of the cutting tools using point cloud data (reverse engineering methodology) for the existing tools.
- v. Perform detailed finite element analysis of the model and if need be, modify the design of the cutting tool.
- vi. Establish relationship between proposed three-dimensional nomenclatures and traditional two-dimensional projected geometry based nomenclatures (if available).
- vii. Establish generic definition and to develop a unified definition of custom-engineered special cutting tool that may be used for numerous downstream engineering and manufacturing applications.

## 5. Custom-Engineered Form Milling (CEFM) Cutter

Milling is one of the most commonly used machining processes in manufacture industry. In the aeronautical sector it represents 70% of overall machining operations. Surface quality of parts and productivity are critical issues in milling processes. Besides, objects like airplane, vehicle, ship, golf club head have complicated profiles involving free form surfaces that need to be manufacture precisely. Machining of these surfaces using conventional ball-end or face- end milling cutters may not lead to the best efficiency of machining and the quality of the machined surface. Machining these free-form surfaces with a custom-engineered (special) form milling (CEFM) cutter is a desirable alternative to obtain the defined shape of the component with improved surface accuracy. That is why in metal cutting industry, the shape of the CEFM cutter is one of the

key factors to affect the machining accuracy and dynamic stability.

A CEFM cutter is a peripheral cutter whose cutting edges are shaped so as to generate a special profile on the surfaces machined. For a single pass, the exact contour of the cutting edge of a form mill is reproduced on the surface of the work piece. This CEFM cutter can be used to machine various hard and soft metals, leathers, woods, etc. to reproduce the desired surface profile. In the case of an insert type form milling cutter, the cutting teeth of the solid type cutter are replaced with the inserts. Here, the body of the cutter is made of one piece of material (low cost steel) and the insert teeth of a different material (normally made of materials like carbide or ceramic). The inserts are generally mechanically locked to the cutter body with the help of wedges and clamps or brazed to it. The major advantage of insert based cutters is that body of the cutter need not be replaced when the insert wears out. There exists a variety of customized form milling cutters designed by the manufacturers on the case to case basis and no standardization in the definition of the CEFM cutter explicitly exist. This chapter deals with brazed insert-based custom-engineered form milling cutter and develops the three- dimensional surface based geometric model of the generic form milling cutter. The proposed definition of the CEFM cutter is generic in nature. Besides, a new CEFM cutter is developed for metal cutting industries.

### 5.1 Model Verification through Reverse Engineering

In this chapter, the accuracy of the proposed model is verified through Reverse Engineering (RE) technique. For this purpose, the digitized point cloud data of the existing CEFM cutter (used in leather cutting industries) is captured with the help of a 3D laser scanner (a)), available at the Institute. Utilizing these point cloud data, surfaces are formed to generate the surface model of the cutter in the surface modeling environment of CATIA (b)). A surface-based model of the same tool is developed with the proposed modeling approach. In order to verify the accuracy of our modeling methodology, surface-surface comparisons are carried out using the surface model developed by the proposed methodology to the surface model generated using point cloud data of the same physical cutter. The deviation plot between these two surface models. The scanning accuracy of the scanner used is  $\pm 0.05\text{mm}$ . The deviation between the corresponding surfaces is around 0.135 mm,

which is negligible and hence the modeling paradigm is validated. Similar exercise can be carried out for a worn or used tool to locate the worn areas on a cutting tool.

## 5.2 Design Improvement and Redesign of the Cutter Model

The 3D model of a cutting tool offers a lot of utility and can provide a variety of down-stream applications. This section presents one such application of redesigning the cutter based on the feedback of the finite element analysis of the CEFM cutter. Besides, two special shaped milling cutters are re-designed for leather and metal industries.

Finite element based engineering analysis (FEA) is performed on the 3D model of the CEFM cutter created using the proposed methodology to optimize its design. This exercise helps in obtaining the optimum values of different angles of the cutter in terms of the least stresses on the cutter teeth to obtain the best milling practice. The CEFM cutter generated in CATIA V5 as described is exported for Structural Transient Dynamic Analysis in ANSYS. ANSYS is an implicit finite element (FE) program which uses the Newmark time integration method for the solution of the transient dynamic equilibrium equation. The cutting insert was analyzed under transient dynamic load conditions while varying the cutter radial rake angle of the insert and insert seat. The nodal solution results of contour plots of stress distribution, deformation and elemental total strain intensity are presented for the insert and its body under a variety of cutter radial rake angles. The CEFM cutter model is modified and optimized based on the feedbacks from the analysis. This is an iterative process and the result is an optimized CAD model of a CEFM cutter.

## 5.3 Special Shaped Milling Cutter Designed for Leather Industries

The CEFM cutter designed for generating shapes on objects made of leather. The cutter is re-designed as per the feedback from the finite element analysis. Material used here for the insert and the cutter body are cemented carbide (WC) and gray cast iron respectively, whose mechanical and thermal properties (a). The insert material has a hardness of 1700HV. The material used for the work piece is ecor sole leather. Its mechanical properties. (b). The cutter is meshed using solid brick 8node45 element. This 3-D brick element is defined by eight nodes having three degrees of freedom at each node,

translations in the nodal x, y, and z directions. The element also has plasticity, creep, swelling, stress stiffening, large deflection, and large strain capabilities. As the geometry of the CEFM cutter is not much complex, so, linear hexahedral (LH) element is referred for mesh generation of the cutter. Hexahedral elements are highly favored and these elements are characterized by high robustness, better mesh quality and require a lower element count to fill a physical domain. Because of their better mesh quality, hexahedral elements have less likelihood to be inverted compared to tetrahedral elements (inversion results in failure of FE analysis). Using LH and quadratic tetrahedral (QT) elements did not evidence significant differences, fact referred by Cifuentes & Kalbag for FE analysis of various structural problems. Various studies reveals that LH, quadratic hexahedral (QH) and QT models all provided acceptable results, even with relatively coarse meshes. LH elements results in fewer degrees of freedom when compared to the QT elements. Thus, they require less CPU time and disk storage. For adaptive meshing in ANSYS, using solid 45 elements, with reduced integration gives good results in solutions that are very accurate. The meshed model is built as a general orthogonal cutting model. The tool is modeled with a fine mesh at the insert, with less refinement at insert seat, while the core cutter body portion is modeled coarsely. During the cutting tests, the cutting conditions are spindle speed,  $N = 150$  rpm, feedrate,  $f = 240$  mm/min for a depth of cut 6 mm and width of cut,  $w = 10$  mm. For our simulation, load has been applied on a single insert in radial and tangential directions. The direction of load application on the cutter.

## 5.4 Multi-Profile Form Milling (MPFM) Cutter

Rotary form tools are increasingly used in machining of 'difficult-to-machine' materials or for general improvement in the productivity of machining operations. Surfaces for components such as dies, vanes, aircraft, car models, etc are usually of very complex (free form) shapes. The surfaces are often produced by a 5-axis CNC machine tool using ball-end or face-end cutters. However, in machining of compound sculptured surfaces with convex and concave shapes, the performance of traditional ball-end mills or face-end mills is usually limited in applications. The errors generated during machining these surfaces with ball-end or face-end cutters are unavoidable. Usually, the scallops generated by the trace of the tool nose in each pass increases the

machining time (indirectly) and deteriorates the surface quality of the machined parts. So, in order to machine multiple sculptured surfaces with reduced machining time and high accuracy of the machined parts, shape design of customized multi-point rotary cutting tool needs to be emphasized. The need is to develop a comprehensive geometric model that could take into account the wide variety of tool geometry and varying machining situation for which the cutter may be used. Moreover, in addition to development of novel customized cutters their accurate 3D models are highly important for the cutting mechanics modeling and machining simulation. In fact, not many significant attempts have been made to develop unified representation schemes that can provide direct 3D models of customized multi-point cutters for downstream technological applications.

## 6. Modeling Algorithm

Based on the above proposed generic definition, a number of form cutters belonging to the family of MPFM cutter can be developed. For a particular parallel (straight) type MPFM cutter, the parameters needed to completely describe this cutter and the relevant data for these parameters to exemplify the methodology. The algorithm that geometrically models a crown type MPFM cutter based on the proposed three-dimensional nomenclature.

Generate the composite cross-sectional curve at one end of the cutter tooth in two-dimensional Cartesian coordinate plane, with center of the MPFM cutter's cross section at one end coinciding with global origin. Generate the composite axial-sectional curve taken at midway along the lateral surface of one of the tooth surface lying on a local right-hand Cartesian frame of reference  $C1 \{O1 : X1, Y1, Z1\}$ . Develop the various cutter tooth surface patches as 1-rail / 2-rail sweep surfaces and ruled surfaces. Generate the final cutter tooth by further surface manipulations like trimming of various surface patches. Develop the surface patches of the body of MPFM cutter. Generate the correct number of cutter tooth's using circular array and form the MPFM cutter model through Boolean operations on these surface patches with respect to the surfaces of the cutter body. Generate the detailed and complete CAD model of the MPFM cutter.

## 7. Experimental Verification

To verify the design of the manufactured MRFM cutter, a series of profile milling tests were performed

over a range of cutting conditions and configurations. This metallic cutter is used for force and torque measurements during an actual cutting operation, using a Kistler-type 9272, four component force-torque measurement dynamometer. In this work, during cutting tests, a part of the cutters' teeth (flank of radius 6 mm) is used for machining and generating the circular (convex) profile on the work piece. The actual cutting forces and torques generated during machining for various cutting configurations are then measured. The same procedure is followed using a traditional concave milling cutter to generate a circular profile of radius 6 mm on the same work piece. In order to verify the strength of the designed MRFM cutter, the forces and torques measured during cutting tests performed on the two cutters are then compared.

## 8. MRFM Cutter

A High Speed Steel MRFM cutter as manufactured with the specifications mentioned used to machine a work piece of dimensions 120x45x35 mm (Length x Width x Height) to generate a circular (convex) profile of 6 mm on the machined surface. The work piece material is mild steel AISI 1020. Experimentally, a conventional horizontal milling machine was used to perform the cutting tests. A four-component force-torque measurement dynamometer was mounted between the work and the machine table to measure cutting forces. The measurement was conducted with 8333 Hz sample rate data acquisition board for duration of 100 seconds. Cutting tests were performed over the range of cutting conditions. The set-up of the cutting experiments with the cutting forces directions acting on the cutting tool. Up (conventional) milling is performed on the milling tests in which the cutter rotates in a direction opposite to the direction of feed. Although the tests were conducted at various depth of cuts and feeds, but only three samples of measured cutting forces and torques.

### 8.1 Concave Milling Cutter

Concave milling cutter is a peripheral cutter whose cutting edge is shaped to produce a convex profile on the surface of a work piece. A High Speed Steel concave milling cutter of standard size 80x6x24x27 mm (outer circle diameter x form radius of the concave / circular cutting edge x width x bore diameter) as referred in IS: 6322-1971 [42] is used to generate a circular fillet profile on a mild steel AISI 1020 work piece (120x45x35 mm (Length x Width x Height)). Instantaneous cutting forces and torque were

measured using a Kistler-type 9272, four component force-torque measurement table dynamometer with 8333 Hz sample rate data acquisition board. Experimental set-up and the cutting conditions are the same as for the cutting tests performed using MRFM cutter. As an example, for an Up Milling operation with concave milling cutter, as per the cutting conditions 1, 10 and 12, the measured cutting forces and torque verses time are presented. concave milling cutter. The experiments indicate that for generating a circular profile (radius 6 mm) on a work piece surface using two different cutters, the measured forces and torque for a novel MRFM cutter are closer to the measured values for a standard concave milling cutter, the maximum cutting forces occurring for all the cutting conditions in the case of a MRFM cutter is much below the maximum values recorded using a concave milling cutter. So, for the same surface finish obtained while machining using both the cutters, the novel design of the MRFM cutter is more robust when compared with the traditional concave milling cutter. Besides, the satisfactory results obtained while comparing the measured waveforms of torque and forces in X, Y and Z directions verifies the design of our novel MRFM cutter. Also, the strength of the designed MRFM cutter is verified while performing the finite element analysis on the cutter.

## 8.2 Utility of MRFM Cutter

The concave cutting edges of the MRFM cutter is designed in view of replacing a number of concave milling cutters of various radii. The MRFM cutter can be used to generate single or multiple circular / convex profiles of variable radii on the work piece surfaces. Various circular profiles of dimensions 2, 3, 4, 5 and 6 mm can be accurately machined on the products' surface. Hence, the utility of the novel design of the MRFM cutter is immense. Machining of such surfaces is greatly required in the industries related to various automotive parts, tubular components, aerospace products, decorative metal and wooden artifacts, leather products, etc. The various convex profiles generated on mild steel and acrylic work piece surfaces respectively. In addition to the robust design of the tool in terms of cutters' strength, the usage of a MRFM cutter is also economical as compared to five different concave cutters required to produce five different circular profiles. Also the cutters' unique design doesn't require any time for its tool changing operation during the generation of various convex profiles

## 9. Result

This chapter concludes the technical sum-up of the thesis work on three-dimensional geometric modeling, design and analysis of custom-engineered milling cutters. The geometric modeling of the cutting tools is an important aspect for the design and manufacturing engineers from the viewpoint of shape realization. The key limitations of the existing definitions of cutting tools is that it prevents the transfer of design information for a range of downstream engineering and manufacturing applications apart from inconvenience in visualization and design verification due to

their dependency on 2D based nomenclature. The stated goal of this thesis is to address these issues, and a novel unified representation scheme is proposed for various conceptual families of cutters that can provide direct 3D generic definitions of custom-engineered (special) cutting tools. Several contributions have been made in pursuit of these goals.

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