International Journal of Machine Tools & Manufacture 104 (2016) 14–25

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

journal homepage: www.elsevier.com/locate/ijmactool

Generalized modelling of cutting tool geometries for unified process simulation

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A R T I C L E I N F O

Article history:
Received 16 October 2015
Received in revised form
18 January 2016
Accepted 21 January 2016
Available online 22 January 2016

Keywords:
Generalized model
Tool geometry
Metal cutting
Process simulation

A B S T R A C T

This paper presents a generalized geometric model of cutting tools for the purpose of predicting the mechanics and dynamics of machining operations. The model starts by defining the tangent and rake face vectors at discrete elements along the cutting edge. The discrete cutting edge elements are assembled mathematically to form either an insert or solid cutting edge, which are further transformed to design turning, boring, drilling, milling and other tools by considering the geometry and kinematics of cutting operations. Homogeneous transformation matrices are used to successively locate and orient the cutting edge within the insert, tool and process coordinate frames. Industry-standard tool-in-use planes are used to obtain the effective geometry for all cutting operations. In total 15 geometric parameters are used for identifying the geometry of an arbitrary tool. Radial and axial runouts are considered in the model. Generalized model is demonstrated by modelling the geometry of sample drills, indexable and serrated milling tools. The generalized model allows unified prediction of machining operations with one mathematical model which covers all operations and tool geometries.

1. Introduction

A typical metallic part is machined mostly using turning, milling, boring and drilling operations with a variety of tools having geometrically defined cutting edges. The geometry of each tool varies depending on the operation and shape of the part, hence the prediction model for each tool – process couple has been uniquely developed in the literature. For example, a roughing end mill may have serrated cutting edge profile and variable pitch to have increased stability; a ball end mill is used to machine parts having sculptured surfaces [1]; multi-functional tools which open a hole, counterbore and chamfer it in one stroke [2]. An indexable cutter may have a custom, unique body shape with distributed inserts both in radial and axial directions [3]. Moreover, the insert geometry may have three-dimensional, unique cutting edge.

The past research presented dedicated mathematical models to predict the metal cutting process performance for each tool–operation combination. However, each machined part needs a variety of tools and operations, and the current practice of developing dedicated models for each metal cutting application limits the use of science-based process simulation and optimization methods in industry. Since the chip shearing process is common for all metal cutting operations, a unified, generalized model is required to adapt any tool geometry and metal cutting operation.

The mechanics of a basic oblique cutting process which is common to all operations with geometrically defined edges are shown in Fig. 1b. The friction and normal forces at the chip-rake face contact zone are predicted as a function of the uncut chip area (A_c) and the cutting force coefficients (K_{uc} and K_{vc}): $F_u = K_{uc}A_c$; $F_v = K_{vc}A_c$. Cutting force coefficients are dependent on the cutting edge geometry and work-material properties [4]; they are either identified from cutting tests or estimated from the cutting mechanics laws based on plasticity models [5,6]. Armarego pioneered the unification of cutting mechanics by proposing the transformation of shear stress, shear angle and average friction coefficient identified from orthogonal cutting tests to oblique cutting edge element (Fig. 1b) [7]. He proposed a model to estimate the cutting coefficients for three dimensional oblique cutting using tool geometry, and demonstrated its application in predicting the forces for turning, drilling and milling geometries [8]. Similarly, Chandrasekharan et al. [9] proposed a general model for predicting drilling forces with arbitrary tool geometry. Their model computes normal rake, cutting edge inclination and cutting edge angles at each oblique cutting edge element. Yucesan et al. [10] modelled the rake face and clearance face (flank) geometry along the cutting edge of ball end mill using three vectors at each

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http://dx.doi.org/10.1016/j.ijmachtools.2016.01.007

Nomenclature

$\mathbf{v}_c(j, k)$	Cutting velocity of tool relative to the workpiece
${}^{\mathrm{I}}\mathbf{i}, {}^{\mathrm{I}}\mathbf{j}, {}^{\mathrm{I}}\mathbf{k}$	Unit axis vectors in Frame I
$\mathbf{P}^{\mathrm{I}}, \mathbf{P}^0$	Array of coordinates and orientation vectors along the cutting edge in Frame I and Frame 0
$\mathbf{p}^{\mathrm{I}}, \mathbf{p}^0$	Points and orientation vectors of each discrete cutting edge in Frame I and Frame 0
$\psi(j, k), \phi(j, k, t), \phi_p(j, k)$	Angular location, instantaneous angular position and pitch angle of cutting edge element S_{jk}
$\kappa_r(j, k), \lambda_s(j, k), \gamma_n(j, k)$	Tool cutting edge, inclination and normal rake angles along cutting edge
$\mathbf{v}_{f,m}, \mathbf{v}_{f,d}$	Assumed feed vectors in milling and drilling operations
$\varepsilon_r(j, k), \varepsilon_a(j, k)$	Radial and axial runout
κ, β, γ	Axial immersion, helix and rake angles along helical flute of the solid tool
$\gamma_f, \gamma_p, \kappa_r$	Cutting edge, axial rake and radial rake angles given by the pocket of toolholder
$N_a(k)$	Actual number of edges at segment k
$Z(k)$	Axial or radial location of segment k measured in Frame 0
$g_l(j, k)$	Binary parameter to check if edge j comes into contact with work material at segment k
${}^0r^{\mathrm{I}}_x, {}^0r^{\mathrm{I}}_y, {}^0r^{\mathrm{I}}_z$	Components of ${}^0\mathbf{r}_{\mathrm{I}}$
a_p	Depth of cut
S_{jk}	Discrete cutting edge element on edge j of segment k
${}^0\mathbf{r}_{\mathrm{I}}$	Frame I origin's position vector relative to Frame 0 origin
${}^{\mathrm{I}}\mathbf{r}$	Position vector which locates each discrete cutting edge in Frame I
$\mathbf{R}^{\mathrm{I}}$	Rotation matrix for each discrete cutting edge in Frame I
$\mathbf{R}^0_{\mathrm{I}}$	Rotation matrix from Frame I to Frame 0
$\mathbf{T}^0_{\mathrm{I}}$	Transformation matrix from Frame I to Frame 0
$A(j,k)$	Axial location of edge element S_{jk} measured in Frame 0
C	Number of points along insert or solid tool
dz	Constant axial or radial thickness of each cutting edge element
K	Total number of discrete axial or radial segments on the tool
N	Number of cutting edges (flutes, inserts or teeth) on the tool
q	Number of segments along tool-workpiece contact zone
$R(j,k), \mathbf{R}^0(j, k)$	Radius and radius vector of cutting edge element S_{jk}
$\mathbf{t}, \mathbf{n}, \mathbf{e}$	Tangent vectors
δ	Width of discrete cutting edge element

point along the tool geometry. They used cutting edge tangent, rake face normal and clearance face normal vectors to set the orientation of the rake face and flank of the tool. However, these methods still require modelling of each geometry individually, hence the mechanics of the cutting process must also be adapted to each tool geometry and process individually. Böß et al. [11] triangulated the rake and clearance faces of insert using its 3D model and calculated the tool angles and forces for milling and drilling operations.

The first attempt in generalizing the geometry of solid end mills and indexed cutters was proposed by Engin and Altintas [12]. They analytically represented the cutting edge geometry of most commonly used milling cutters. Han-Min [13] and Grzesik [14] used ISO-standard definitions to work on the kinematics of oblique cutting operation. Their models are descriptive to help understanding the industry-standard geometry. The details of standard tool geometry for turning and drilling tools can be found in [15]. In addition to tool in hand and tool in use systems, Astakhov [15] introduced tool in machine system to emphasize the importance of the toolholder geometry and the positioning of the cutting edge relative to the axis of rotation. Kaymakci et al. [3] used ISO-standard definitions to unify the geometric models of indexable tools. Campocasso et al. [16] modelled the geometry of turning inserts by using homogeneous transformation matrices to place the insert on tool holder. They extended the model to predict cutting forces for turning and drilling operations with indexable tools [17]. Tunc et al. [18] modelled the five-axis milling operation using an arbitrary tool geometry and predicted the forces from thermo-mechanical model of the material. Although previous literature give a great insight into modelling the geometry and mechanics of individual operations, they do not consider all tool geometries and machining operations in a unified mathematical model.

This paper presents a unified geomeric modelling of solid and indexable tools which is later used in generalized prediction of cutting forces, vibrations and dimensional surface errors generated on the part. The geometric model is intended to be used in generalized cutting process models.

Henceforth, the paper is organized as follows: The modelling of the cutting edge location and its rake face orientation vectors for solid and indexable tools with arbitrary geometry is presented in Section 2. The application of the proposed general geometry is demonstrated for turning, boring, drilling and milling tools in Section 3. The paper is concluded in Section 4.

2. Generalized geometric model of cutting tools

Solid tools, such as end mills and twist drills, may have helical, serrated cutting edges with varying diameter. The inserts may have varying cutting edge and rake surface, and they may be distributed on the cutter body in various ways depending on the application, surface finish quality and process stability [19]. The model must be general enough to consider all geometric variations on the tool.

It is assumed that any cutting edge geometry can be constructed by assembling series of small, differential elements as illustrated in Fig. 1, for indexable cutters, and Fig. 2, for solid tools. Each element may have as small as few micron differential length if the edge is curved with varying geometry, or can be larger if the edge geometry and rake face remain constant. Each edge element is defined by placing a point at its mid point, and can be oriented via tangent vectors to assign rake, helix or side cutting edge angles. Since the cutting mechanics need only the coordinates of points and angles along the cutting edge, there is no need to consider the whole solid model of the tool. The assembly process is carried out by sequential transformation of differential elements as follows.

2.1. Indexable cutter

The coordinate system (Frame I) of an insert is placed at its seat centre, and the differential edge elements are assembled along the cutting edges of an insert (Fig. 1a). Insert is digitized along its cutting edges by series of points. The tangent vectors (**t**, **n** and **e**) define the orientation of each differential edge segment; they are