International Journal of Machine Tools & Manufacture 82-83 (2014) 42–49

Contents lists available at ScienceDirect

International Journal of Machine Tools & Manufacture

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

Identification of the specific cutting force for geometrically defined cutting edges and varying cutting conditions

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ARTICLE INFO

Article history:
Received 19 December 2013
Received in revised form
25 March 2014
Accepted 31 March 2014
Available online 13 April 2014

Keywords:
Specific cutting force
Force prediction
Mechanistic force modeling
Dexel model
Determination of undeformed chip thickness
Non-standard tools

ABSTRACT

Cutting force modeling is a major discipline in the research of cutting processes. The exact prediction of cutting forces is crucial for process characterization and optimization. Semi-empirical and mechanistic force models have been established, but the identification of the specific cutting force for a pair of tool and workpiece material is still challenging. Existing approaches are depending on geometrical idealizations and on an extensive calibration process, which make practical and industrial application difficult. For nonstandard tools and five axis kinematics there does not exist a reasonable solution for the identification problem.

In this paper a co-operative force model for the identification of the specific cutting forces and prediction of integral forces is presented. The model is coupled bidirectionally with a multi-dexel based material removal model that provides geometrical contact zone information. The nonlinear specific forces are modeled as polynomials of uncut chip thickness. The presented force model is not subjected to principal restrictions on tool shape or kinematics, the specific force and phase shift are identified with help of least square minimization. The benefit of this technique is that no special calibration experiments are needed anymore, which qualifies the method to determine the specific forces simultaneously during the machining process. In this paper, experiments with different cutting conditions are analyzed and systematically rated. Finally, the method is validated by experiments using different cutting conditions.

1. Introduction

Force modeling has a long tradition in modeling cutting processes, because cutting force directly affects workpiece quality. In the course of increasing computing capacity, approaches in modeling cutting processes have been changed in the last few years. Material removal simulations accelerated with rendering engines have recently become popular [1,2]. Moreover, a global trend to virtual manufacturing with the aim to optimize the whole process chain can be observed. The prediction of forces has lost none of its significance, for most optimizations the forces are the first aspect in the modeling chain. Exemplary applications are the prediction of chatter, tool deflection and thermomechanical workpiece behavior [3–5]. Empirical and mechanistic force models are of great importance for industrial manufacturing [6], but the determination of specific forces and cutting coefficients is still challenging and does not take advance of modern numerical and geometrical simulation approaches.

The main drawback of empirical force models is the extensive calibration process for each pair of tool and workpiece material. Different authors propose the evaluation of a set of experiments with special requirements. Basically, there are three different ways in the calibration process. Basic mechanics of cutting can be applied if a series of orthogonal cutting experiments are evaluated [7]. Another way is to evaluate milling experiments and equating average cutting forces per tooth with measured data [8,9]. The third and most practical method uses instantaneous forces and numerical approximation of force coefficients [10–12]. In recent work, forces are calculated with the help of a dexel model and a gradient method for the determination of cutting coefficients [13]. The development of the identification process clearly shows a migration to digital processing. Refs. [7–13] are dedicated to a special tool geometry (indexed and helical cutters, ball and tapered end-mills) and the linear two component model $K_c hb + K_e b$ is used. The proposed models follow the same modeling procedure: the tool geometry is used to determine characteristic angles, like the helix lap angle α, the axial and radial immersion angle ϕ and κ. A coordinate transformation on the basis of these angles and process kinematics is used to transform the unstationary forces in tool coordinates to the stationary coordinates of the measurement system. This is crucial for all identification methods of cutting constants. A key role in evaluating force models is the precise determination of

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http://dx.doi.org/10.1016/j.ijmachtools.2014.03.009
0890-6955/

undeformed chip thickness. The nominal undeformed chip thickness $h = f_t \sin(\phi + \alpha) \sin\kappa$ is a well known approximation for the undeformed chip thickness. It is used by most authors even though it lacks accuracy for trochoidal tool paths and is not applicable with 5-axis kinematics.

In this contribution a non-iterative identification method for nonlinear specific forces and time synchronization with measured forces is presented for the first time. The technique combines a nonlinear empirical force model with computer based material removal calculation and is designed as a black box solver within virtual manufacturing environments. A force operator which maps the specific force to the resulting force is proposed. Applying the operator, makes a prediction of forces possible. Applying the operator in an inverse way, allows the identification of specific forces from measured data.

The proposed model is pure virtual, all data is generated with help of dexel based computer algorithms. Therefore, no restrictions on tool shape are made and the model is not depending on parametric approximations of a general tool. Furthermore, no approximation of undeformed chip thickness is made, actual engagement conditions are identified with help of dexel based contact zone analysis. Tool movement is controlled by G-Code through virtual simulation of the entire process.

The paper is structured as follows: in the next section a brief overview of the simulation environment and the determination of the contact zone is presented. Furthermore, a detailed tool analysis is made. In Section 3 the force model and the identification of the specific cutting forces are presented. Finally, in Section 4 the experimental validation and discussion are presented.

2. Simulation environment

Deduced from the introduction, existing simulation environments based on Boolean material removal algorithms have to be generalized to bridge a gap in the field of NC-Simulation based force prediction. Especially the geometrical complexity of the tool in combination with more complex movements like 5-axis milling, ramping or circular milling depend on a new modeling approach.

The material removal process and the contact zone analysis are based on the kinematic movement of the tool that is controlled by the NC-Simulation-System CutS [3]. Therefore, a kinematic model of the machine tool with linear and rotational axes and a tool spindle is built up, including realistic movements with accelerations and jerks. For every axis a transformation matrix exists that describes the translation and rotation from one axis to another. All these transformations are concentrated into one matrix, which is referred by the time depending kinematic matrix K in the following. Caused by the fact, that the measurement of cutting forces is made in the workpiece coordinate system, this matrix is used to transform the cutting forces from the tool coordinate system into the workpiece coordinate system.

2.1. Determination of undeformed chip thickness

In [2] a CutS based method of contact zone analysis, related to the cutting edge of the tool is introduced. The tool described by a STEP-file is discretized along the cutting edge in equidistant areas and the triangulated functional face, the rake face, is modeled. The specialty of this method is the cutting edge orthogonal triangulation of the functional rake face. This allows a cutting edge orthogonal analysis of the contact zone and thus a better individual reproduction of the real process especially in the area of the corner radius. Based on a dexel based material removal simulation the contact zone is identified by the intersection of the modeled rake face and dexel elements. The detected dexel cut points (DCPs) are analyzed afterwards. The DCP is transformed in a cutting edge segment individual coordinate system (b, h), which is orthogonal to the cutting edge. The undeformed chip thickness for a single cutting edge element is defined as the maximum distance of a DCP orthogonal to the cutting edge. Thereby the influence of the macro geometry, especially the rake and helix angle, is considered using the exact representation of the rake face. This is a major benefit using a model of the real tool instead of an ISO standard tool. This method is used for the determination of the undeformed chip thickness in this modeling approach and allows a realistic contact zone analysis for complex tool geometries. The contact zone analysis is not the scope of this paper, but discussed in detail in [2].

2.2. Tool analysis

The processed information also allows a detailed analysis of the tool shape. Therefore, the tool reference plane $P_r(i)$ for every discretization segment of the cutting edge is constructed and the difference to the real rake face is calculated. The difference can be described in two different directions, along the cutting edge and orthogonal to the cutting edge. These characteristics are called rake angle γ and inclination angle λ_s. Furthermore, the cutting edge can be characterized by the lap angle ψ, compare Fig. 1. The tool is analyzed along the cutting edge sections which are in contact during complex machining operations like ramping or circular milling. These sections are the main, minor and the undercut cutting edge. The plot in Fig. 2 shows that in comparison to a standard ISO insert, the three characterizing angles of a cutting edge and even the derivation of the angles along

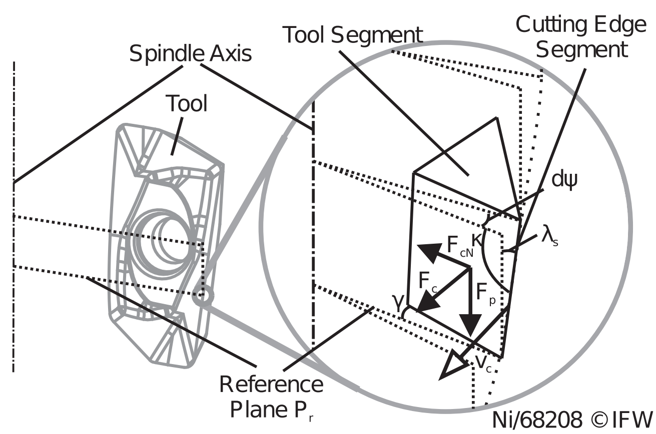
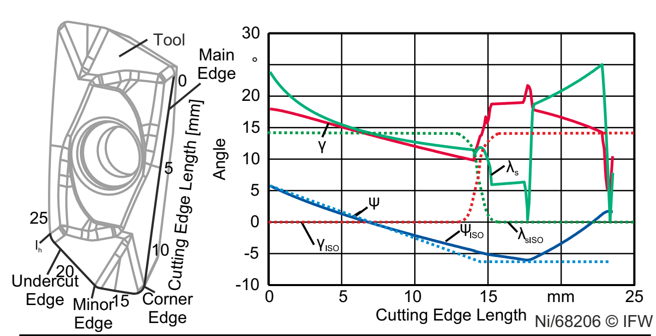


Fig. 1. Adaption of the tool macro geometry.



Angle	Variation [°]		Derivation [°/mm]	
Rake Angle γ	4.61	21.69	-43.24	36.46
Inclination Angle λ_s	0.21	25.02	-69.34	66.28
Lap Angle ψ	-6.03	5.77	-1.14	1.95

Fig. 2. Tool analysis, variation of characteristic angles.