Theory and Practice of Science and Technology
2025, VOL. 6, NO. 9, 62-65
DOI: 10.47297/taposatWSP2633-456912.20250609

Research on Cutting Force Influence Simulation of Virtual CNC Turning

Chunlei Li

Department of Precision Manufacturing, Suzhou Institute of Industrial Technology, Suzhou, Jiangsu, 215104, China

ABSTRACT
Sources and measurement of cutting forces are studied to establish the steady-state cutting force prediction model. Modeling of work piece machining error is analyzed, a simplified process coordinate system is established, and the mathematical solving model of machining error within the work piece is given. The cutting force due to work piece bending deformation is studied, a work piece deformation factor error model is established based on steady-state cutting force and the prediction simulation of cutting forces and machining error is achieved.

KEYWORDS
Physical simulation; Virtual CNC turning; Cutting force; Machining error modeling

1 Introduction

If there were no machining errors, the actual geometric model after virtual machining would align with the theoretical geometric model. However, due to various machine tool errors and physical errors during the machining process, the actual cutting points do not match the theoretical points, and the distance between them constitutes the machining error.

There are many factors that affect machining errors, such as geometric and motion errors inherent in the machine tool itself. These errors cause the actual tool tip trajectory to deviate from the ideal trajectory dictated by CNC instructions, ultimately manifesting in the part's shape. Such errors are primarily determined by the actual relative positions of the tool and workpiece during the cutting motion. Physical errors primarily arise from various physical changes occurring during the cutting process. For instance, tool wear itself can exceed the dulling limit, affecting the surface quality of the workpiece; chips of various shapes generated during cutting may wrap around the tool, reducing the surface roughness of the workpiece; heat produced by the machine tool and the cutting process can cause thermal deformation of the workpiece; cutting forces may induce elastic deformation and vibrations in the workpiece. Therefore, it is essential to study and establish machining error models in virtual machining to better utilize virtual machining for researching actual machining processes. Physical simulation of virtual cnc turning focuses on the object's physical properties impact on the machining process; it can reflect and fit the nature of actual machining process [1]. As the highly nonlinear, seriously random interference and uncertainties of the machining process, the all factors modeling is very difficult.

Cutting force in cutting process is very important physical quantities, which directly determines the cutting heat generation, affecting the tool wear, damage, life, work piece machining accuracy and machined surface quality. Therefore, this paper studies on physical simulation based on cutting force.

2 Cutting force model

In actual turning, the primary factor affecting the shape and dimensions of the workpiece is the distance between the tool tip and the machining center of the workpiece. This distance changes instantaneously and is referred to as the instantaneous radius. The instantaneous radius is formed through multiple dimensional loops. For ease of analysis, the machine tool is treated as a rigid body, and the errors are assumed to follow the principle of superposition. Coordinate systems are established on key components such as the tool holder, workpiece, spindle, and guideways. Finally, the instantaneous radius is derived through coordinate transformation, and the difference between this radius and the ideal radius of the workpiece represents the final machining error. Cutting force from three aspects, to overcome the resistance of the elastic deformation, to overcome the plastic deformation resistance, to overcome the friction of chip on the tool rake face and the friction between tool flank face and the transition surface. Usually cutting force is decomposed into three mutually perpendicular forces, as shown in Figure 1.

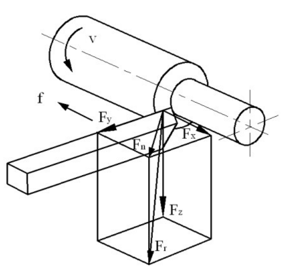

Figure 1 Composition of cutting force

Where, F_Z is the tangential force. It is tangent to the transition surface and perpendicular to the base surface. It is necessary to calculate the tool intensity, design tools and determine the machine power. F_X is the feed force. It is parallel with the axis of the work piece. It is necessary to design the feed mechanism and calculate the feed power. F_Y is the resistance force of cut depth. It is perpendicular to the axis of the work piece. It is used to determine the deflection of the work piece and the intensity of machine parts and turning tools.

According to Taylor empirical formula, the three forces can be indicated by the index formula as given below [2].

$$F_Z = C_{Fz} a_p^{x_{Fz}} f^{y_{Fz}} v^{n_{Fz}} K_{Fz}$$
$$F_y = C_{Fy} a_p^{x_{Fy}} f^{y_{Fy}} v^{n_{Fy}} K_{Fy} \quad (1)$$
$$F_X = C_{Fx} a_p^{x_{Fx}} f^{y_{Fx}} v^{n_{Fx}} K_{Fx}$$

Where,C_{Fz},C_{Fy},C_{Fx} are the coefficients determined by metal to be processed and cutting conditions; $a_p$is cut depth; $f$is feed rate; $v$is cutting speed x_{Fz},y_{Fz},n_{Fz},x_{Fy},y_{Fy},n_{Fy},x_{Fx},y_{Fx},$n_{Fx}$are the index of cut depth, feed rate and cutting speed; K_{Fz},K_{Fy},K_{Fx} are the correction factor when the actual processing conditions do not match the conditions of the empirical formula obtained. These coefficients can be obtained through cutting experiments.

3 Machining error model

In order to significantly facilitate the subsequent detection procedures and in-depth analytical work of machining processes, this paper first puts forward a set of reasonable basic assumptions based on the common characteristics of mechanical manufacturing scenarios. Specifically, it assumes that all the machine parts involved in the machining process are rigid bodies - this means that during the entire machining cycle, the parts will not undergo any form of elastic deformation, plastic deformation, or other dimensional changes caused by external forces, temperature fluctuations, or material fatigue, which lays a stable foundation for the accuracy of subsequent error analysis. At the same time, the paper also assumes that there is no mutual interference between each individual error source. In other words, the errors generated by different components (such as the radial runout of the spindle, the straightness error of the guide rail, and the wear error of the tool) will not affect or overlap with each other. This assumption simplifies the complexity of error superposition and makes the subsequent error calculation more feasible.

On the basis of the above assumptions, this paper adopts a modular grouping strategy for the complex process dimension chain. According to the functional attributes and structural characteristics of each component in the machining system, the entire process dimension chain is divided into several independent and clear groups. These groups respectively correspond to the key components that play a core role in the machining process, including the workpiece (the final processing object), the spindle (the component that drives the workpiece or tool to rotate), the guide rail (the component that ensures the linear movement accuracy of the tool or workpiece), and the tool (the component that directly processes the workpiece to form the required shape and size). After completing the grouping, the paper further establishes a separate and independent coordinate system for each group. These coordinate systems take the geometric center, reference plane, or key positioning points of the corresponding components as the origin, and define the X, Y, Z axes according to the movement direction and processing requirements of the components. Through the reasonable setting of these coordinate systems, the positional relationship and dimensional parameters between each group can be accurately described, and finally, a complete and closed process dimension chain is formed - this closed chain ensures that all dimensional information in the machining process can be effectively transmitted and associated, without missing any key links.

In this closed process dimension chain, the final size of the workpiece (including parameters such as length, diameter, height, and surface roughness that meet the design requirements) is defined as the closure ring of the size chain. The closure ring is the final result of the entire machining process and the core indicator that reflects whether the machining quality meets the requirements. All other dimensional parameters in the size chain (such as the runout of the spindle, the clearance of the guide rail, and the length of the tool) serve as the component rings that affect the closure ring.

The biggest advantage of this grouping and coordinate system establishment method lies in its ability to effectively disperse the large number of individual errors that may affect the machining precision. In the actual machining process, there are numerous error sources, and if these errors are directly analyzed as a whole, it will be difficult to identify the key error factors and calculate the error magnitude accurately.

However, by grouping the components and establishing independent coordinate systems, each individual error can be attributed to the corresponding group, realizing the "separation and classification" of errors. After completing the error dispersion, the paper further uses coordinate conversion technology to integrate all the individual errors into the unified process coordinate system. This coordinate conversion process involves operations such as translation, rotation, and scaling of the coordinate systems of each group.

By converting the error parameters in each group's coordinate system into the process coordinate system, all errors can be converted into the same reference system for unified calculation. Finally, through the superposition and calculation of these integrated errors in the process coordinate system, the final integrated processing error of the workpiece can be accurately obtained. This integrated processing error directly reflects the deviation between the actual processing size of the workpiece and the design size, providing a reliable basis for optimizing the machining process, adjusting the equipment parameters, and improving the machining precision.

The specific structure and parameter settings of this simplified process coordinate system, including the origin position, axis direction, and coordinate scale of each group's coordinate system, as well as the conversion relationship between the group coordinate systems and the process coordinate system, are clearly shown in Figure 2.

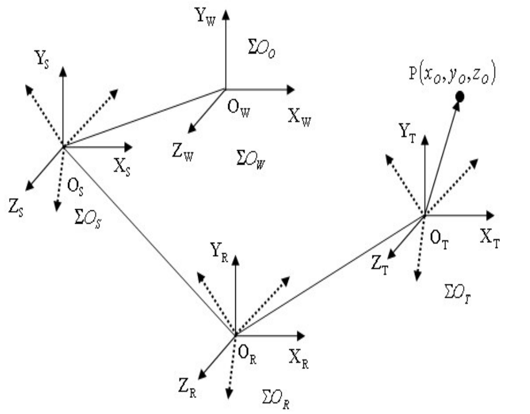

Figure 2 Simplified process coordinate system

Where, ΣO_W is the work piece coordinate system; it is set on the installation datum of the work piece and used to determine the work piece location. ΣO_S is the spindle coordinate system; it is set on the installation datum of the spindle and used to determine the installation error of work piece, fixture and spindle rotation accuracy. The installation error of work piece and fixture determines the deviations of work piece coordinate system relative to the spindle coordinate system. ΣO_R is the rail coordinate system; it is used to determine errors associated with the rail. ΣO_T is tool coordinate system; it is set on the nose of tool and used to determine the static regulation error during tool installation and the dynamic adjustment error relative to process coordinate system during tool movement on the rail. Errors caused by elastic deformation, cutting heat, vibration, tool wear and other physical factors can also be discussed in tool coordinate system. ΣO_O is the process coordinate system, it can be established anywhere in the scene, but in order to facilitate the process, it can be coincide with the ideal work piece coordinate system. Solid line represents the ideal coordinate system; dashed line represents the actual coordinate system, which is formed by translation and rotation of the ideal coordinate system caused by various errors. In fact, transformation between the ideal coordinate system and its actual coordinate system generated by the error is very small, in order to simplify the diagram, the origin of two coordinate systems are coincident. The coordinate of point P is the coordinate of the work piece instantaneous center in the process coordinate system

In order to obtain the actual size of the work piece, transform vector $r_{O_T P}$ from ΣO_TtoΣO_O,the formula is given below.

$$r_{O_o p} = T_{O_S} T^{"}_{O_S} T_{O_R} T^{"}_{O_R} T_{O_T} T^{"}_{O_T} r_{O_T P} \tag{2}$$

Where, $T_{O_S}, T_{O_R}, T_{O_T}$are transformation matrixes between all ideal coordinate systems; $T^{"}_{O_S}, T^{"}_{O_R}, T^{"}_{O_T}$ are transformation matrixes between ideal coordinate systems and actual coordinate system; $T^{O_T}_{O_O}$is the transformation matrix of total error.

D-H method is used to solve the transformation matrix of total error; D-H method is generally used to determine the robot's hand position and posture [3]. The coordinate transformation from i coordinate system to $i-1$coordinate system is equivalent to $i-1$coordinate system rotates α angle around x axis, pans $l$along axis; then rotates β angle around y axis, pans $m$along y axis; finally rotates γ angle around z axis, pans n along z axis to i coordinate system, transformation matrix is given below.

$$T = Rot(x,\alpha)\,Trans(l,0,0)\,Rot(y,\beta)\,Trans(0,m,0)\,Rot(z,\gamma)\,Trans(0,0,n) \tag{3}$$

Homogeneous coordinate's representation is given below.

$$T = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha & 0 \\ 0 & \sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & l \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\beta & 0 & \sin\beta & 0 \\ 0 & 1 & 0 & 0 \\ -\sin\beta & 0 & \cos\beta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$
$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & m \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 & 0 \\ \sin\gamma & \cos\gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & n \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{4}$$

The actual work piece size can be obtained by putting the transformation matrix of total error into equation (2).

4 Work piece deformation factor error model

A work piece deformation factor error model is established based on steady-state cutting force. Three-jaw chuck is simplified as a fixed end, the end of thimble is simplified as a movable hinge bearings.

When the end thimble is not used for processing, the entire process system can be simplified as a cantilever beam model, the calculation diagram is shown in Figure 3. When turning a slender shaft, the end thimble at the other end is used as an auxiliary support to reduce distortion, the calculation diagram is shown in Figure 4.

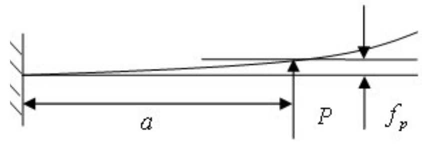

Figure 3 Calculation diagram without end thimble

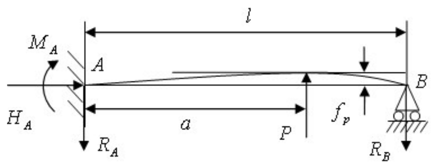

Figure 4 Calculation diagram with end thimble

Where, *a*is the distance of cutting point from the chuck; *P*is cutting depth resistance force at the cutting point; f_p is the deformation at the cutting point. $f_p$can be solved by force balance equation.

5 Summary

In order to verify the model, a virtual turning simulation system is developed on VC6.0 platform with OpenGL. When turning a slender shaft, but the end thimble at the other end is not used, it is shown in Figure 5. Finished work piece shows significant bell shape, which is consistent with the conclusions of the real processing, as shown in Figure 6.

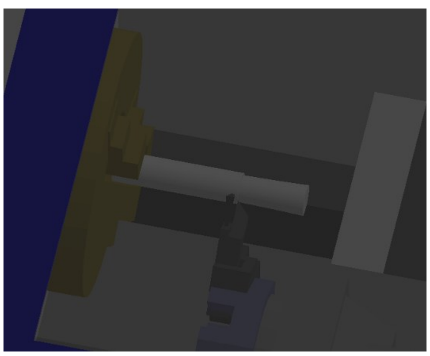

Figure 5 Virtual turning slender shaft

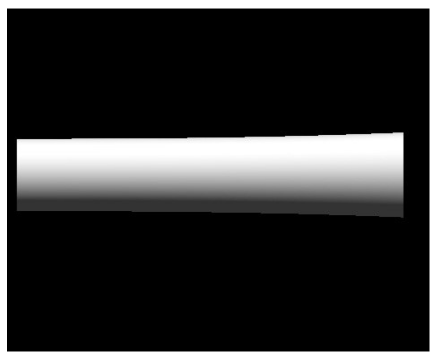

Figure 6 Finished work piece

Funding

The numerical control machining process design of slider inserts (NO: SIITHT2025006789)

About the Author

Chunlei Li, master, lecturer, mainly engaged in teaching and research of advanced manufacturing technology.

References

[1] Sheng Liang, Liao Wenhe, Initial study on key technology of physical simulation of numerically controlled machining, Journal of System Simulation, Vol.15 (2003), p.631.

[2] Chen Riyao, Metal cutting theory, Machinery Industry Press, 2002, p.56.

[3] Chen J S.A, Study of Thermally Inducing Machine Tool Errors in Real Cutting Conditions. Machine Tools Manufacture, 36(2005): p.1401.