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Evaluation of the stiffness chain on the deflection of end-mills under cutting forces

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Abstract

This study presents the investigation of the stiffness of the system formed by the machine-tool, shank and toolholder, collet and tool. Cutting forces induce the deflection of the system, and consequently an error appears on the machined surface.

Comparing values obtained from cantilever beam models applied to the cutting tool, analytical or FEM, with those experimentally obtained, large differences have been observed, which in some cases are more than 50%. For this reason, we have proceeded to evaluate the stiffness of each of the existing elements between the machine bed and the tool tip. Thus, deflections of the machine-tool, toolholder and toolholder clamping in the spindle, tool clamping in the toolholder, and tool itself, were measured experimentally under the effects of known forces.

The final application is the ball-end milling of complex surfaces, an operation commonly performed in the finishing of moulds or forging dies, where errors of more than 70 μm are not unusual. A great part of this error comes from the deflection of the machine-tool assembly, spindle, shank and tool, due to the high cutting forces of the high speed machining of tempered steels. Cutting forces can be estimated using a semi-empirical approach, and from here some values of probable errors may be taken into account to check if the CNC programs are sufficiently adapted. However, a previous study of the deflection chain in the cutting process is needed, as is presented in this work.

Results show that stiffness of the slender and flexible tools is 15 times lower than that of the machine and toolholder system. But this correlation is only 5–7 times lower for shorter and thicker tools.

Keywords: Complex surfaces; High-speed machining; Moulds; Milling; Machining errors

1. Introduction

To achieve the finishing requirements of the mould sector, HSM technology has to minimize the effect of various factors [1–3] producing dimensional errors. Error can be understood as any deviation in the position of the mill cutting edge from the theoretically programmed to produce a part of the desired tolerance. Such factors include those deriving from the CAM stage [4], owing to the approximation of the toolpaths produced by current commercial software to the desired surface, those resulting from insufficient resolution of the CNC control loops relating to the choice of both feed forward and look-ahead parameters. There are also errors due to the construction and stiffness of the actual machine-tools [5], which are directly related with vibration in machining, inertial tool-path inaccuracy and thermal distortions. Various problems may derive from the tool-clamping systems [6,7], or from thermal deflection [8] of the workpiece and of the tools.

Finally there are important errors addressed to the deflection of cutting tools (or distortion of the entire machine under the action of the cutting force) which is looked at in the present paper. In tests [9], errors derived from tool deflection in ball-end finishing processes exceeded 40 μm, and more than 100 μm are collected in [10] with a radial depth of cut of 1 mm. In end milling of a wrought aluminium alloy with a 6∅ mm tool, errors of 170 μm are described in [11] when an axial depth of cut of 10 mm is used, although this $a_p/\varnothing$ correlation is somewhat

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Notation

a_r	radial depth of cut
a_p	axial depth of cut
V_c	cutting speed
f_z	feed per tooth
HSM	high speed machining
STC	Shank, toolholder with Tapered Collet
SCC	Shank, toolholder with Cylindrical Collet
E	Young's modulus
I	second moment area
I_{TS}	second moment area of the tool body
I_{TT}	second moment area, teeth(flute)-zone section of the tool
D	tool diameter
δ	tool deflection, perpendicular to tool axis
δ_m	maximum tool deflection, perpendicular to tool axis
$\delta_{\theta c}$	deflection, perpendicular to tool axis, due to the angular deflection of the toolholder clamping in the spindle nose
$\delta_{\theta h}$	deflection, perpendicular to tool axis, due to the angular deflection of the tool clamping in the toolholder
δ_1	measured deflection at the distance L_1
δ_2	measured deflection at the distance L_2
δ_3	measured deflection at the distance L_3
δ_4	Measured deflection at the distance L_4
δ_{dif}	Difference in the measurement due to the angular deflection of the tool clamping
L_C	distance from the spindle nose to the toolholder nose
L_1	distance to the first measurement point
L_2	distance to the first measurement point
L_3	distance to the first measurement point
L_4	distance to the first measurement point
L_F	distance to the force application point
L, L_H	tool overhang, L when is used in a generic sense
L_s	distance to the sensor measurement point
L_{TS}	length of the tool body
L_{TT}	length of the tool teeth(flute)-zone
F	force
F_Y	force in Y axe
F_m	maximum force
θ_c	angular deflection due to the toolholder semi-rigid clamping in the spindle
θ_h	angular deflection due to the tool semi-rigid clamping in the toolholder
θ_T	angular deflection of all the system, without the machine-tool effect
M_c	torque at the shank (toolholder) clamping in the spindle nose
M_h	torque at the tool clamping in the toolholder
K_{sr}	stiffness of tool at the sensor point
K_p	stiffness of tool at the tool tip, inverse to Cp flexibility of tool at the tool tip
$K_{\theta c}$	stiffness angular coefficient of the toolholder clamping in the spindle
$K_{\delta c}$	stiffness radial coefficient of the toolholder clamping in the spindle
$K_{\theta h}$	stiffness angular coefficient of the tool clamping in the toolholder
$K_{\delta h}$	stiffness radial coefficient of the tool clamping in the toolholder
$K_{\theta T}$	stiffness angular coefficient of the equivalent system without the machine-tool
$K_{\delta T}$	stiffness radial coefficient of the equivalent system without the machine-tool
$K_{\theta S}$	stiffness angular coefficient of all the system
$K_{\delta S}$	stiffness radial coefficient of all the system
$K_{\delta M}$	stiffness radial coefficient of the machine-tool at the spindle nose
R^2	regression factor

unrealistic. Deflection errors are critical where tolerances in the die and mould industry are concerned, which are commonly in the range 0.05–0.1 mm for stamping dies and less than 0.04 mm for injection moulds.

The deflection errors of the tool cannot be solved with an improved design of the machine-tool as they are induced by the tool edge–material interaction. Therefore, a machine with a high repeatability, and even with very good precision, will be not the solution for this lack of accuracy in the machined forms.

An appealing model [12–14] for the study of tool deflection is that in which the tool is regarded as a cylindrical cantilever beam. Deflection then conforms to the equation

$$\delta = \frac{64}{3\pi}\frac{F}{E}\frac{L_H^3}{D^4} \tag{1}$$

It may thus be seen in Eq. (1) that tool deflection in the static model is a function of the following three parameters, E is the Young's modulus for the tool material, L_H^3/D^4 is the tool slenderness parameter. D is the equivalent tool diameter and L_H is the overhang length. F is the cutting force perpendicular to the tool axis. Surface errors would be deduced by the component of deflection (δ) in the transverse direction to the inclined surface (α), obtained as ($\varepsilon = \delta \cdot \text{sen}\alpha$).