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Experimental studies of cutting force variation in face milling

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ABSTRACT

The purpose of this paper is to present a developed cutting force model for multi-toothed cutting processes, including a complete set of parameters influencing the cutting force variation that has been shown to occur in face milling, and to analyse to what extent these parameters influence the total cutting force variation for a selected tool geometry. The scope is to model and analyse the cutting forces for each individual tooth on the tool, to be able to draw conclusions about how the cutting action for an individual tooth is affected by its neighbours.

A previously developed cutting force model for multi-toothed cutting processes is supplemented with three new parameters; eccentricity of the spindle, continuous cutting edge deterioration and load inflicted tool deflection influencing the cutting force variation. A previously developed milling force sensor is used to experimentally analyse the cutting force variation, and to give input to the cutting force simulation performed with the developed cutting force model.

The experimental results from the case studied in this paper show that there are mainly three factors influencing the cutting force variation for a tool with new inserts. Radial and axial cutting edge position causes approximately 50% of the force variation for the case studied in this paper. Approximately 40% arises from eccentricity and the remaining 10% is the result of spindle deflection during machining. The experimental results presented in this paper show a new type of cutting force diagrams where the force variation for each individual tooth when two cutting edges are engaged in the workpiece at the same time. The wear studies performed shows a redistribution of the individual main cutting forces dependent on the wear propagation for each tooth.

1. Introduction

Face milling is an important industrial cutting process, used widely in manufacturing industries of various types, because of its efficiency and its possibility of creating complex geometrical shapes. In the view of the increasing demands on the manufacturing accuracy as well as process efficiency and cost, the milling process is under constant development. By developing the milling process towards increased accuracy, there is a potential of increase in sustainability in the production system by eliminating process steps, e.g. grinding operations, after the milling process. The success of such development work is dependent on deep and detailed knowledge of the process behaviour.

The milling process has received significant attention in the relevant literature over a long period of time. Already in 1941 Martellotti [1,2] laid the foundations for a mathematical description of the tool path in milling. Within recent years researchers have shown increasing interest in factors that can affect the cutting forces involved. A force model introduced by Fu et al. [3] includes a parameter termed runout ε, comprised of factors, such as radial throw, spindle-out-of-roundness, that can cause variations in the radial position of the cutting edge. Kim and Ehmann [4] have presented a force model including factors that affect the chip thickness. They have chosen to model three separate factors in the radial direction: cutting edge position, eccentricity and spindle tilt. These two models provide a rather adequate account of the face milling process. There is also important work such as that of Kline and DeVor [5], which has dealt with shank-end mills, and of Ber [6], Lee et al. [7] and Budak and Altinas [8] concerned with spindle deflection.

Despite the considerable work done on the measurement of milling forces, there are only few studies in which force measurements have been obtained with anything other than a Kistler dynamometer. The fact that the Kistler dynamometer registers the total force applied in three orthogonal directions, and that it is frequently used for cutting force analysis, may well explain the fact that most researchers in this area employ force models concerned with cutting forces in these same three orthogonal directions. There are two studies, however, in which

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strain gauges were used for cutting force registration. Ikezaki and Takeuchi [9] describe equipment involving optical data transmission for registering forces acting on a rotating tool. Theirs is a one-channel system having a transmission speed of 22 kHz in serial form that is 2750 Hz in 8 bits in parallel form. Doolan et al. [10] in turn, have mounted a strain gauge on the clearance face for studying the entry of a single tooth, machining with only one tooth at a time. Albrecht et al. [11] presents a capacitance displacement sensor mounted on the tool holder with the purpose of registering high frequency cutting forces. They reported that they were able to increase the bandwidth from 350 to 1000 Hz with the use of an indirect sensor.

A milling force sensor measuring the cutting forces with strain gauges mounted close to each insert on a modified face milling tool, has been developed by Adolfsson (maiden name) et al. [12]. The purpose of the sensor is to measure the cutting forces acting on each individual cutting edge to be able to study cutting force variations.

A basic mechanical cutting force model is also presented by Adolfsson (maiden name) et al. [13], including four parameters (radial and axial deviations in cutting edge position, cutting edge deterioration and eccentricity) affecting the cutting force variation multi-toothed cutting processes. This paper presents a developed cutting force model also including the effects of tool inclination and tool deflection.

In this paper the milling force sensor is used to verify the developed cutting force model with experimental studies of the face milling process. All of the six parameters influencing the cutting force variation are analysed. It is also shown that the milling force sensor presented in [13] makes it possible to analyse the effects when more than one cutting edge is engaged with the workpiece at the same time. Since the cutting forces contains the key information needed to monitor and troubleshoot and simulate the milling process, the aim of the work presented in this paper is to contribute with high quality cutting force information trough both a developed multitooth cutting force model and measured data for each individual cutting edge on the tool.

2. List of symbols

The following is a list of the metal cutting related symbols employed in the study and the terms to which they refer.

ΔA_{spi}	Deviations in the uncut chip cross-sections	mm^2
a_e	Radial cutting depth	mm
a_p	Axial cutting depth	mm
b_1	Undeformed chip width	mm
b_e	Equivalent chip thickness	mm
c_i	Errors due to eccentricity	mm
C_r	Cutting resistance	N/mm^2
C_1	Slope of the main cutting force producing chip thickness	N/mm
C_2	Intersection of the main cutting force producing chip thickness	N
C_{r1}	Parameter determining C_r	–
C_{r2}	Parameter determining C_r	–
d_{VB}	Geometrical changes due to VB	mm
e_{rc}	distance between tool centre point and centre of rotation	mm
e_t	Pitch	mm
f	Feed rate	mm/rev
F_c, F_T	Main cutting force	N
F_f, F_A	Feed force	N
F_p	Passiv force	N
F_b	Bending force	N
h_1	Undeformed chip thickness	mm
h_{1i}	h_1 for a given cutting edge i	mm
h_{1n}	Nominal undeformed chip thickness	mm
h_{1ui}	h_1 due to defelction of the spindle	mm
h_e	Equivalent undeformed chip thickness	mm
k_u	Spring-rate deflection	m/N
k_r	Spring-rate deflection	m/N·min
n	Rotational speed	rpm
n_{na}	Number of subsequent teeth not in contact with the workpiece	
r_i	Radial positional error	mm
v	Cutting speed	m/min
v_f	Feed speed	mm/min
v_0	Cutting speed without retardation	mm/min
VB	Flank wear	mm
z	Number of teeth	
α	Relief (clearance) angle	°
β	Wedge angle	°
γ	Rake angle	°
δ_b	Spindle deflection	mm
φ_{fc}	Load function, F_f/F_c	–
φ_{pc}	Load function, F_p/F_c	–
θ	Cutting edge position	deg.
Γ_e	Angle of eccentricity	deg.

3. Mechanical cutting force model

In [13] a basic cutting force model includes 4 factors:

- radial and axial position errors,
- eccentricity,
- wear.

influencing the cutting force variation for each individual cutting edge on the tool. The factors are illustrated in Fig. 1. In the mechanical cutting force model employed, each cutting edge in contact with the workpiece are subjected to a load, a magnitude of which is basically dependent on the workpiece material and of the chip cross section area. The load is divided into three orthogonal cutting force components, calculated as:

$$F_c = C_r h_1 b_1 \tag{1}$$

$$F_f = \varphi_{fc} F_c \tag{2}$$

$$F_p = \varphi_{pc} F_c \tag{3}$$

where F_c is the tangential or main cutting force, F_f is the radial or feed force and F_P is the axial or passive force. The parameters φ_{fc} and φ_{pc} are factors relating the feed and the passive forces to the main cutting force. The cutting resistance C_r of the workpiece material is defined as ratio of the main cutting force in relation to the uncut chip cross section.

$$C_r = \frac{F_c}{h_1 b_1} \tag{4}$$

Since experiments have shown that the main cutting force is linearly dependent on the undeformed chip thickness, the