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Procedia CIRP 77 (2018) 287–290

www.elsevier.com/locate/procedia

8th CIRP Conference on High Performance Cutting (HPC 2018)

An optimization methodology for material databases to improve cutting force predictions when milling martensitic stainless steel JETHETE-M152

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Abstract

A material database for JETHETE-M152 was developed applying a novel methodology for improving the precision of cutting forces. This approach defines a variable specific edge force depending on the feed rate and cutting edge geometry. Applying this methodology, accurate predictions could be obtained when using complex shape inserts with different micro-geometries or with feed rates lower than the cutting edge radius. These predictions showed an improvement compared to those of the strategy of keeping constant the specific edge coefficient.

Furthermore, an orthogonal to oblique transformation technique was applied to predict the cutting forces in face and side milling. The results showed good agreement with experimental results.

Keywords: Modelling; Forces; Cutting Edge, Milling; JETHETE-M152.

1. Introduction

Modelling of machining operations can help manufacturing industries by improving machining performance and efficiency. Contrary to finite element models, mechanistic models or orthogonal to oblique transformations are less time consuming.

Mechanistic models consist of performing experimental tests similar to the operation to be modelled, and collect the information in a database, as done by Gradisek et al. [1], Lamikiz et al. [2], Ge et al. [3] and Min et al. [4]. A database developed by Yucesan and Altintas [5] was composed of equations defining the specific cutting forces depending on the rake angle, feed rate, axial depth of cut and tool geometry. However, this kind of method is only valid for a cutting operation the same as the experimental tests.

The orthogonal to oblique methodology consists of performing orthogonal cutting experimental tests (the simplest cutting operation) and applying a mathematical model to predict cutting forces for any cutting operation. This is the methodology used by Altintas and Lee [6], Popovic et al. [7], Lazoglu [8], Aksu et al. [9] and Ipilakyaa [10].

The databases used in orthogonal to oblique transformations are composed of equations for chip compression ratio, shear stress, friction angle and specific edge forces. This last parameters have been considered constant by some researchers, as it is suitable for simple shape inserts and feed rates higher than the cutting edge radius. However, for inserts with complex micro-geometry or when machining with feed rates lower than the cutting tool radius, imprecise predictions can be obtained.

In this research, an optimization methodology was developed to improve cutting force predictions, by identifying the influence of the micro-geometry of complex shape inserts on the cutting forces. Using this methodology, a variable specific edge force depending on the uncut chip thickness was obtained. A material database detailed by equations defining

10.1016/j.procir.2018.09.017

the chip compression ratio, shear stress, friction angle and the aforementioned specific edge forces was then developed. Finally, an orthogonal to oblique mathematical transformation was applied, aiming to predict the cutting forces for face and side milling.

Nomenclature

F_c, F_f, F_p	cutting, feed and penetration forces	k_{ce}, k_{fe}, k_{pe}	specific edge force (cutting, feed and penetration)
F_x, F_y, F_z	cutting forces broken down into X, Y and Z directions	k_{cc}, k_{fc}, k_{pc}	specific cutting force (cutting, feed and penetration)
γ	rake angle	β	friction angle
f	feed rate	τ_s	shear stress
h_c	cut chip thickness	η_c	chip flow angle
v_c	cutting speed	h	uncut chip thickness
r_e	cutting edge radius	r_c	chip compression ratio
Z	number of teeth	a_p	depth of cut
R^2	coefficient of determination	i	inclination angle

2. Database development

The database was developed according to Fig. 1. The first step was to carry out the orthogonal experimental tests (set-up 1, Fig. 1). These were performed by turning a tube and measuring cutting forces and chip thicknesses. The second step was to develop the database, where a linear fitting of cutting forces against uncut chip thicknesses was required. The novelty of this work consists on breaking down the fitting into the micro-geometry of the insert. The third step was the validation of the model. After performing some preliminary tests in oblique conditions, a series of face milling (set-up 2, Fig. 1) and side milling tests (set-up 3, Fig. 1) were carried out to compare the experimental cutting forces with those of the models.

2.1. Orthogonal tests

Orthogonal turning tests were performed to create the database. The cutting conditions are summarized in Table 1 and the experimental set-up in Table 2. These tests are linked to the set-up 1 Fig. 1.

Table 1. Cutting conditions of orthogonal turning tests.

v_c (m/min)	f (mm/rev)	a_p (mm)	r_e (µm)
200	0.001, 0.002, 0.003, 0.004, 0.005, 0.0075, 0.025, 0.03, 0.05, 0.075, 0.1, 0.2, 0.3, 0.4	2	37

Table 2. Orthogonal turning tests set-up.

Input variables	Experimental set-up	Output variables
v_c f a_p γ r_e	**Machine:** Lagun CNC vertical machining center (CNC 8070). **Tool insert:** Walter ODMT060512-D57. **Test material:** JETHETE-M152 **Acquisition system:** Kistler 9121 dynamometer. **Measuring chip thickness:** Micrometer. **Coolant:** Dry condition.	F_c F_f h_c

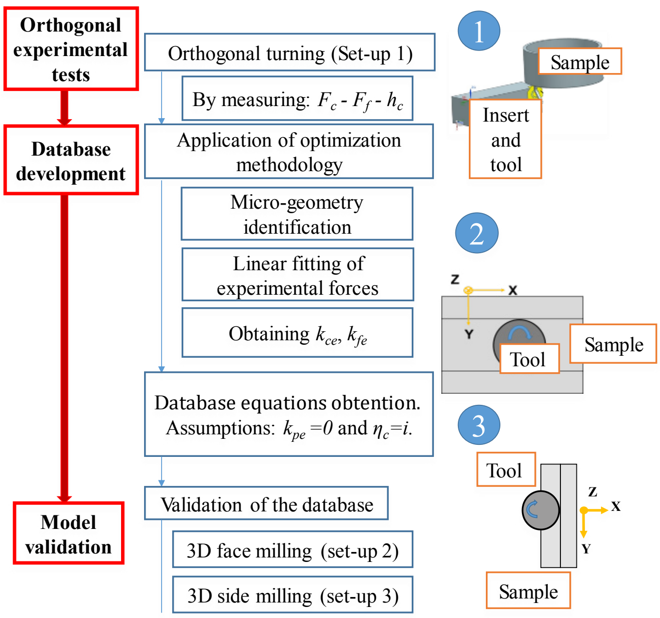

Fig. 1. Flow diagram of the research work.

2.2. Optimization methodology

Once the experimental tests were carried out, the optimization methodology was applied to calculate the specific edge forces. Feed forces were employed due to the sensitivity to the cutting edge changes.

The micro-geometry of the insert was relatively complex. The cutting edge radius r_e was 37 µm ± 2 µm (measured in Alicona confocal profilometer IFG4). The rake angle value changed at a distance of 0.1 mm from the cutting edge, i.e., -8º for a lesser distance and 8º for a greater distance (see Fig. 4).

The methodology consisted of fitting linearly the feed forces of the three highest feed rates (0.2, 0.3 and 0.4 mm/rev), obtaining the slope and the coefficient of determination R^2 (see Fig. 2).The value of R^2 was closed to 1 (0.997 for cutting forces and 1 for feed forces).

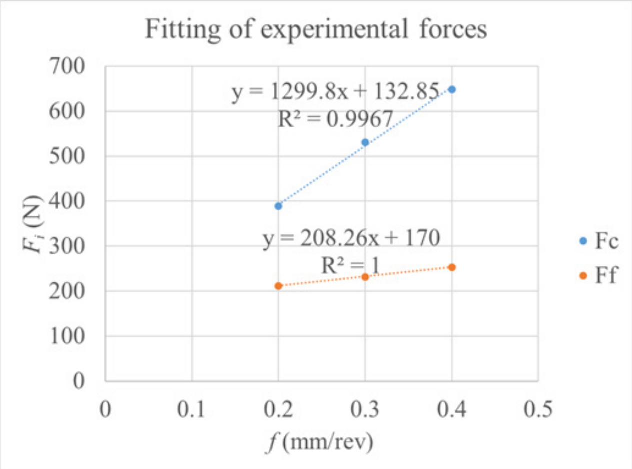

Fig. 2. Fitting of the forces at 0.2, 0.3 and 0.4 mm/rev.

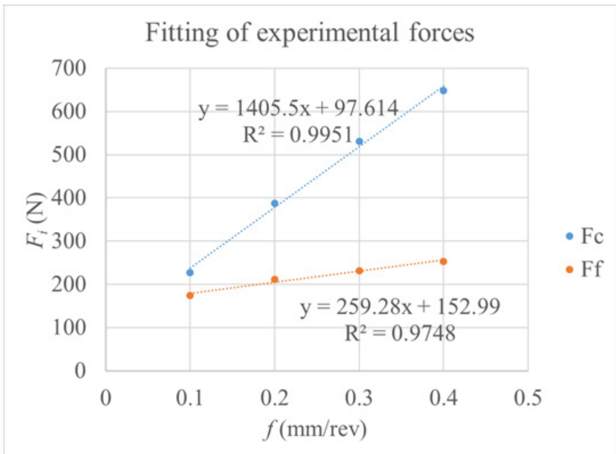

Fig. 3. Fitting of the forces at 0.1, 0.2, 0.3 and 0.4 mm/rev.

When the forces corresponding to the feed rate of 0.1 mm/rev were added to the fitting (see Fig. 3), the slope of the feed force fitting changed by 20% and R^2 was 0.9748. These differences could be due to a change in the micro-geometry of the insert at 0.1 mm.

Following the methodology, the rest of the experimental tests were added one by one, repeating the calculus for each case. At the end of the process, two more changes were detected in the slope, at 0.03 mm and 0.005 mm from the tip of the edge radius, which could be related to the beginning of the cutting edge radius and the minimum chip thickness respectively [11].

In order to validate these assumptions, the micro-geometry of the insert was measured in Alicona confocal profilometer IFG4 and compared with the trend of the experimental feed forces (see Fig. 4). It was confirmed that the change detected at 0.1 mm corresponded to the variation of the rake angle from 8º to -8º. At a value of 0.03 mm due to the tool radius, the value of the rake angle began to decrease profressively. In order to simplify the methodology, the feed forces below 0.03 mm were linearly fit in two zones, divided at 0.005 mm.

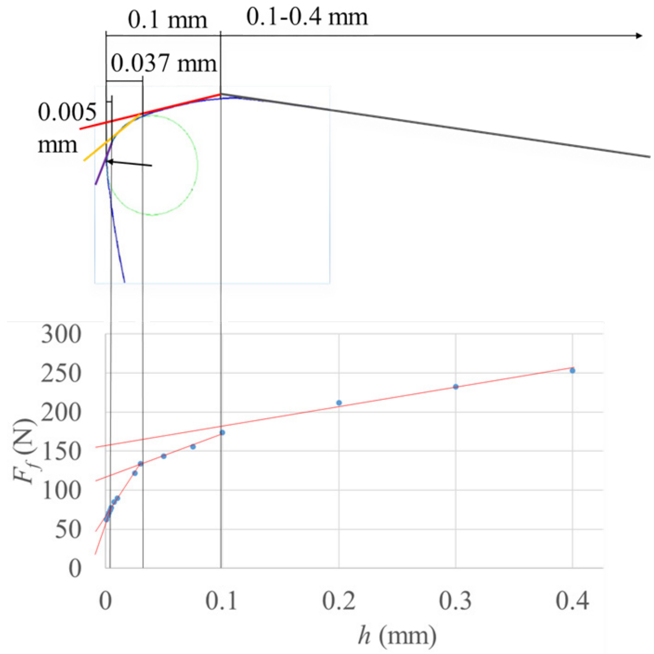

Fig. 4. Comparison between the geometry of the Walter ODMT060512-D57 insert and the values of the orthogonal experimental feed forces.

Table 3. Database for JETHETE-M152.

$\tan(\beta)$	$0.3488 - 0.333 \cdot h + 0.5717 \cdot \gamma$
τ_s	$555.8 - 354.6 \cdot \gamma - 85.58 \cdot h$
r_c	$(0.7138 + 0.4991 \cdot \gamma) \cdot h^{(0.1324+0.1125\gamma)}$
k_{ce} (N/mm)	h < 0.0050 mm → 26.3 h >= 0.005 mm & h< 0.03 mm → 39.5 h >= 0.03 mm & h< 0.1 mm → 52.8 h >= 0.1 mm → 97
k_{fe} (N/mm)	h < 0.0050 mm → 59.2 h >= 0.005 mm & h< 0.03 mm → 68.7 h >= 0.03 mm & h< 0.1 mm → 116.2 h >= 0.1 mm → 152
k_{pe} (N/mm)	0 (Armarego and Whitfield [13])

2.3. Database development

Using the linear fittings, specific edge forces (k_{ce}, k_{fe}, k_{pe}) were obtained for each micro-geometrical zone, and finally, equations from literature were used to obtain the material database (Budak et al. [12]). The results are shown in Table 3.

Once the database was obtained, the specific cutting forces (k_{cc}, k_{fc} and k_{pc}) were calculated applying the equations from the literature (Budak et al. [12]).

3. Validation

In order to validate the database, face and side milling experimental tests were performed (see Fig. 1 set-up 2 and set-up 3) and the results were compared with those modelled (see Fig. 5 for face milling and Fig. 6 for side milling).

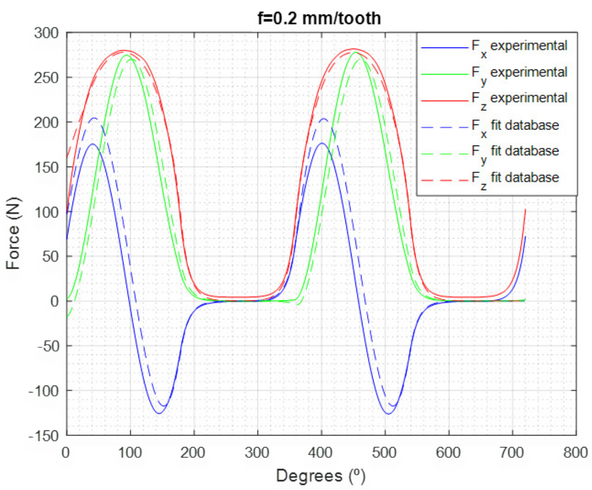

Fig. 5. Experimental and fit database forces for face milling.

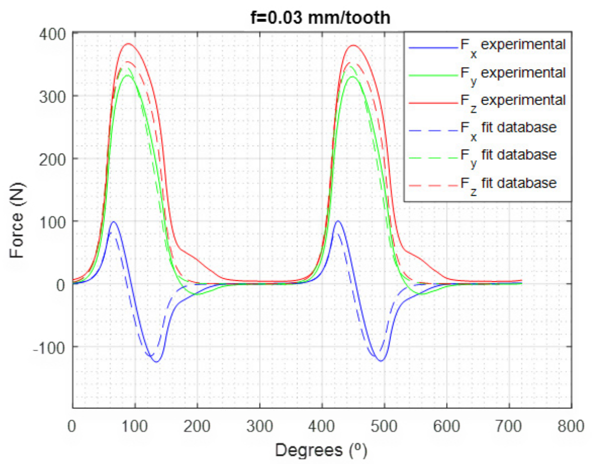

Fig. 6. Experimental and fit database forces for side milling (climb).

In order to show the improvements in the accuracy of the predictions, cutting forces were also modelled using a standard database. The results were compared using the root mean square (RMS) of the experimental forces and those modelled (see Table 4). Cutting conditions were v_c = 200 m/min and Z=1 for both operations; for face milling a_p= 0.5 mm, f= 0.2 mm/z and 40 mm immersion; and for side milling a_p= 2 mm, f= 0.03 mm/z and 20 mm immersion.

Table 4. RMS comparison for milling experimental and modelled forces.

Operation	Comparison	RMS (N)
Face milling v_c = 200 m/min, Z=1, a_p= 0.5 mm, f= 0.2 mm/z	Experimental-Fit database	9.8
	Experimental-Not fit database	16.5
Side milling v_c = 200 m/min, Z=1, a_p= 2 mm, f= 0.03 mm/z	Experimental-Fit database	17.1
	Experimental-Not fit database	51.5

RMS comparison results showed better agreement with a fit database. For instance, in side milling with f_z=0.03 mm/z the error was reduced from 51.5 N to 17.1 N when compared to the experimental results. Moreover, the maximum and minimum values were better predicted, and the trends were also accurately modelled.

4. Conclusions

The presented methodology proved to be effective in optimizing material databases to improve cutting force predictions. Furthermore, it identified the effect of micro-geometry of complex shape inserts over the forces. In this way, a variable specific edge force dependent on the feed rate was obtained. Applying this in a material database, forces for face and side milling were accurately predicted.

Acknowledgements

The authors would like to thank to H2020 and to the Basque Government for the financial support given to the projects MC-SUITE (H2020 GA: 680478) and SMAPRO (KK-2017/00021).

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