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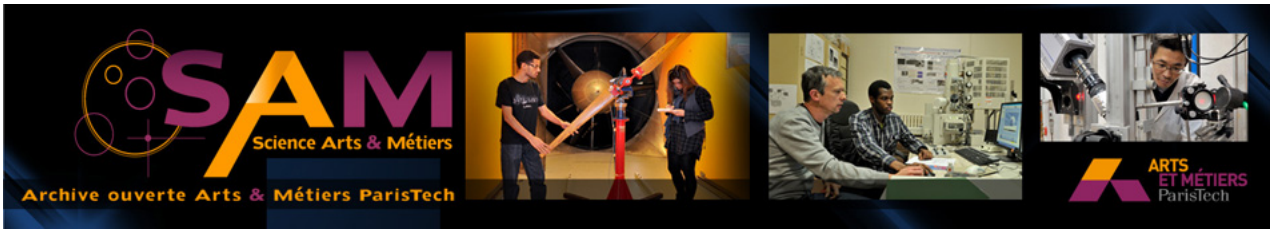

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Cutting Forces Prediction in the Dry Slotting of Aluminium Stacks

J. Salguero[1,a*], M. Calamaz[2,b], M. Batista[1,c], F. Girot[3,d], M. Marcos[1,e]

[1]Faculty of Engineering, University of Cadiz. C/ Chile 1, E11002 – Cadiz (SPAIN)

[2]Arts et Métiers ParisTech, Esplanade des Arts et Métiers, F33405 – Talence (FRANCE).

[3]University of the Basque Country, ETSI, Alameda de Urquijo s/n, E48013 – Bilbao (SPAIN)

[a*]jorge.salguero@uca.es, [b]madalina.calamaz@ensam.eu, [c]moises.batista@uca.es, [d]franck_girot@ehu.es, [e]mariano.marcos@uca.es

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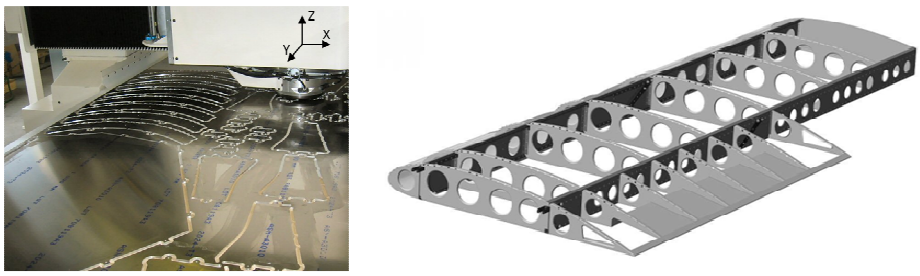
Abstract. Cutting forces are one of the inherent phenomena and a very significant indicator of the metal cutting process. The work presented in this paper is an investigation of the prediction of these parameters in slotting processes of UNS A92024-T3 (Al-Cu) stacks. So, cutting speed (V) and feed per tooth (f_z) based parametric models, for experimental components of cutting force, $F(f_z,V)$ have been proposed. These models have been developed from the individual models extracted from the marginal adjustment of the cutting force components to each one of the input variables: $F(f_z)$ and F(V).

Introduction

Knowledge of cutting forces is very important because it leads to an efficient machining process through the proper selection of operating parameters, machine tools, fixtures, and tools. Furthermore, cutting force monitoring is frequently used to detect tool wear and breakage, among others [1].

On the other hand, High Speed Contour Milling (HSCM) is a widely used machining process in the aeronautical industry, being applied for the production of structural elements, by slotting the external contour of plain workpieces. This process is habitually applied to high dimensions stacks of aluminium sheets, in order to maximize the manufacturing process productivity, and is commonly performed in gantry type machines with a treading head, tooling equipment which presses the sheets, avoiding the axial displacement when the head is moving in the XY plane, at a constant depth of cut. Later, the slotted pre-forms are plastically shaped and finished in a previous stage to assembly, Fig. 1.



a) b)

Fig. 1. a) High Speed Contour Milling process. b) Wing frame made with aluminium alloys.

The challenge in accurately modeling the cutting forces of a machining process lies in the fact that the cutting process is very complex, due to the many highly interlinked variables influencing these forces [1]. Therefore, machining processes are strongly dependent on a high number of variables and parameters (input), such as cutting speed, feed, depth of cut, tool material and geometry, lubrication and cooling conditions, which also has a considerable influence on the final

workpieces quality. This influence is usually reflected in other variables and parameters (output), such as forces, temperature and tool life/wear.

So, cutting force is one of the most relevant output variables since the information that can provide for the machining process evaluation [2]. This owes to that cutting forces depends on all the input variables and parameters; so, according to Axinte and Sanchez [3,4], this relationship can be written as:

$$F = F\,(w_1,\ldots, w_q, tg_1,\ldots, tg_p, tm_1,\ldots, tm_r, LR, r_1,\ldots,r_n, f, V, d) \quad (1)$$

In this equation, w_i are the parameter related to the material to be machined; tg_i and tm_h are the parameters related to the cutting-tool material and geometry; LR represents the lubrication and cooling conditions; finally, r_i are variables associated with the machining process and the rest of the cutting conditions.

Eq. 1 is hardly controllable due to the high number of variables that take place in it. However, if some pre-established conditions, such as lubrication, tool and cutting depth (d), are fixed for a specific process of a specific material, this equation can be reduced to only two variables: feed-rate (f) and cutting speed (V), making easier its control. So, in this case, Eq. 1 can be transformed to:

$$F = F\,(f, V) \quad (2)$$

Precisely, HSCM is one of the machining processes in which cutting forces can be expressed by Eq. 1 or, more simply, by Eq. 2.

Empiric-experimental parametric models are commonly obtained from the mathematical adjustment of experimental data to pre-established math functions. These models are useful for approximating and predicting the output variables when input variables change. So, in particular, parametric exponential models have shown a good adjustment for macro-geometrical deviations, such as straightness and parallelism in the dry turning of aluminium alloys [5]. However, in the same processes, potential models present the best adjustment for other output variables such as roughness or cutting forces [6,7].

Experimental procedure

Machining tests have been carried out in a Fatronik Hera machining center, equipped with a Siemens Sinumerik 840D Numerical Control.

Tests were performed by machining 10 mm wide and 40 mm length slots (in full immersion, without floor), on five 170x100x2 mm^3 UNS A92024-T3 sheet stacks. In order to obtain a high environmental performance, slots were performed in absence of cutting fluids [8], using the cutting parameters included in Table 1.

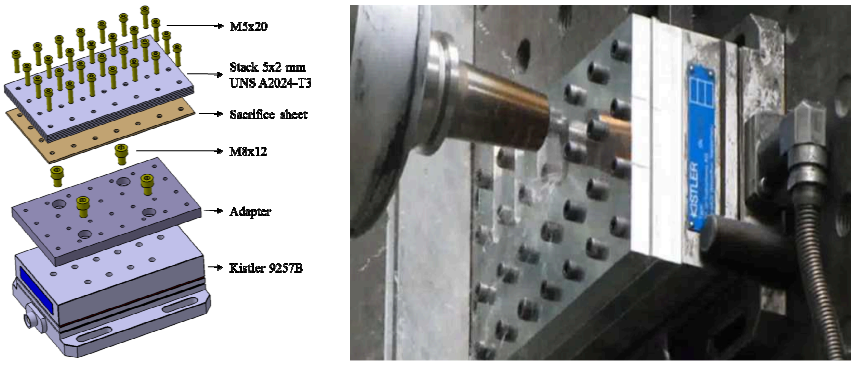
Table 1. Machining parameters applied to the HSCM process.

V [m/min]	503	565	628	691	754	817
f_z [mm]	0.035	0.050	0.065	0.080		

Aluminium stacks were prepared for being coupled to a Kistler 9257B dynamometric table through the mechanical joint of stacks to an adapter, so reducing axial displacements and simulating the effect of a treader head, Fig. 2.

A 10 mm diameter end-mill, WC-10Co (K30 micrograin), with 2 teeth (γ=17º, α =20º) and helix angle 30º, was used in the milling tests, being coupled to a thermal contraction HSK-50 tool-holder.

Cutting forces have been acquired at a frequency of 20 kHz, using a National Instruments DAQCard-6062E board and a BNC-2110 multiplexor. Acquisition and translation of the triaxial cutting force components (F_x, F_y, F_z) was programmed using the development platform LabView.

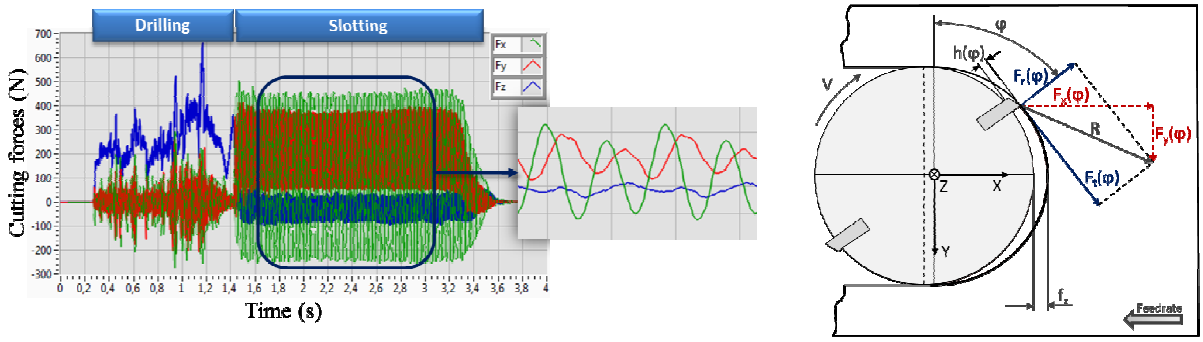


a) b)

Fig. 2. a) Experimental set-up. b) Slotting 5x2mm stack.

Results and discussions

Fig. 3 plots typical cutting force orthogonal component records. Two zones can be distinguished in this figure. First of them corresponds to the initial input drilling process, conducted at a half of the programmed feed-rate (notice that F_Z has a similar behavior in the drilling process of each sheet of the stack). Second zone is the corresponding to the 40 mm slotting process, and the tool way out. The analysis has been centered in this pseudo-stationary zone, where the average value of each component has been calculated.



a) b)

Fig. 3. a) Cutting forces evaluation zone (framed). b) Cutting force components in slotting.

In the framed zone, F_X shows a behavior near to sinusoidal, characteristic of the milling processes, with positive values when the tool spin-turn angle (φ) is between 0 and π/2 (up-milling), and negative values when φ is between π /2 and π (down-milling) [9]. F_Y component has positive values due to the reference system used.

On the other hand, F_Z negative values indicate that the positive helix angle of the cutting-tool generates axial forces, which trends to get up the sheets and to provoke separations between the interfaces in a form approximately periodic during the process. It must be also noticed that, as it can be expected, F_Z values are much lower than those corresponding to F_X and F_Y. Additionally, it can be stated that the spring-back in the material compressive direction is the responsible of the gap between the maximum and minimum values of F_X and F_Y components. In parallel, the gap in F_Z can be associated to the vertical response of the sheets that configure the stack, and that do not respond to an average distribution as F_X and F_Y.

Fig. 5 plots the cutting force orthogonal components average values as a function of the cutting speeds for each feed per tooth applied.

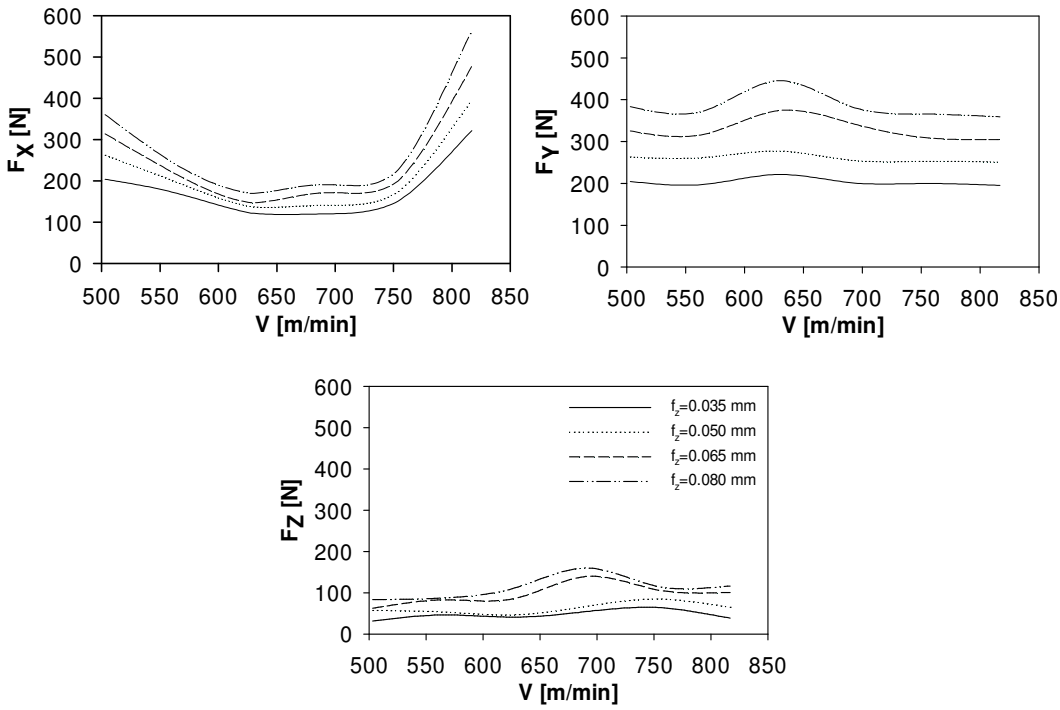


Fig. 5. Evolution of the force components, as a function of cutting speed (V) for different feeds (f_z).

It can be noticed that $F_N(V)$ curves (N=X,Y,Z) show a light displacement with f_z. On the other hand, $F_N(f_z)$ curves show a tendency to increase for each cutting speed. According to [6,10], a potential model can be proposed for the marginal distributions of the cutting force components as functions of feed per tooth, Eq. 3:

$$F_N = a\, f_z^{\,b} \tag{3}$$

However, $F_N(V)$ is different depending on the cutting force component. In effect, for F_Y and F_Z components, some stability can be appreciated with only a light increasing. According to [6,10], it allows proposing potentials models as the Eq. 4. Thus:

$$F_N = a\, V^b \tag{4}$$

In this way, F_Y and F_Z can be modeled as a potential function, in which coefficient and exponent values, a, b and c, can be calculated by linearizing, by translating to logarithmic scale, Eq. 5:

$$F_N = a\, V^b\, f_z^{\,c} \;\rightarrow\; \log(F_N) = \log(a) + b\log(V) + c\log(f_z) \tag{5}$$

This equation corresponds to a plane in the log (F_N) - log (f_z) - log (V) space. A multilinear regression has been applied for determining a, b and c values of the independent terms of the parametric model, Eq. 7 (Table 2).

$$F_N' = a' + bX + cY \tag{7}$$

Table 2. Coefficient and exponents of the potential model for F_Y and F_Z

	a	***b***	***c***	R^2
F_Y (N)	5751.64	-0.11	0.78	0.95
F_Z (N)	7.57	0.86	1.13	0.82

Notice the good adjustment and the good approximation of the model to the experimental data, Fig. 6.

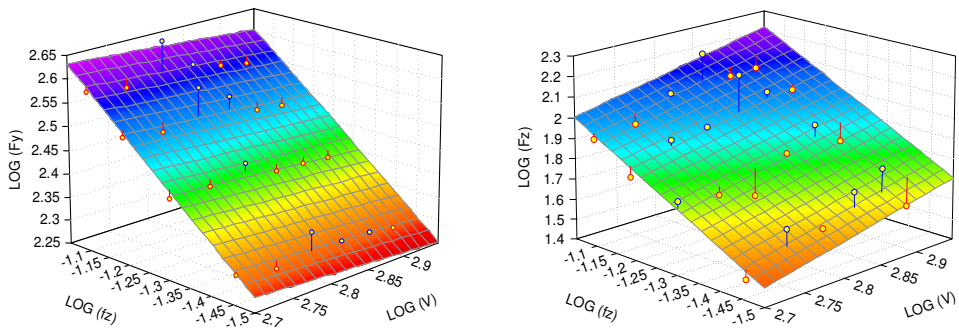


Fig. 6. Regression planes log(F_N) - log(f_z) - log(V) for F_Y and F_Z.

On the other hand, the evolution of F_X as a function of V is noticeably different to those observed for F_Y and F_Z, Fig. 5. It can be noticed that F_X has a minimum value extended in a range of values of V. This fact is characteristic of HSCM and it allows defining the cutting speed range where F_X is minimal for each feed per tooth value. Firstly, a bi-parabolic convolution model could be considered. In order to simplify this model for taking an unique theoretical minimum, a parabolic model can be proposed, Eq. 8:

$$F_X = a + bV + cV^2 \tag{8}$$

Coefficients and exponents of the marginal models $F_X(f_z)$, Eq. (4), and $F_X(V)$, Eq. (8) are included in Table 3. The good adjustment allows proposing a combined parabolic-potential model, Eq. 9.

Table 1. Adjustment values for marginals $F_X=af_z^b$ and $F_X=a+bV+cV^2$

	f_z [mm]				**V [m/min]**					
	0.035	*0.050*	*0.065*	*0.080*	*503*	*565*	*628*	*691*	*754*	*817*
a	2591.4	3496.8	4362.5	5201.5	2072.5	644.5	426.4	819.4	770.3	3067.4
b	-7.7	-10.5	-13.2	-15.8	1.5	2.5	2.5	1.7	2.0	1.5
c	0.006	0.008	0.010	0.012	n/a	n/a	n/a	n/a	n/a	n/a
R^2	0.89	0.91	0.92	0.92	0.99	0.99	0.95	0.98	0.99	0.99

$$F_X = (a + bV + cV^2)\, f_z^d \tag{9}$$

Table 4 includes the values of the coefficients and exponent of the combined model of Eq. 9. Notice the good adjustment of the model to the experimental data, Fig. 7.

Table 4. Adjustment values for the combined model of the Eq. 9.

	a	***b***	***c***	***d***	***R^2***
F_X (N)	23671.46	-71.46	0.056	0.62	0.92

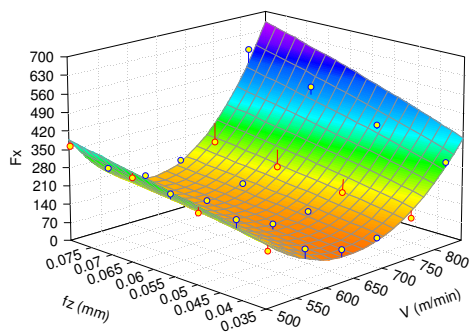


Fig. 7. Coons adjustment surface $F_X(f_z,V)$

Conclusions

This paper has reported on the results of a study of the influence of cutting speed and feed per tooth on the orthogonal components of cutting force acquired in slotting processes of Al-Cu sheets stacks.

Z cutting force component, F_Z, has shown a value lower than the recorded for F_X and F_Y. This has been associated with the dependence on the stacked sheets separation. On the other hand, F_X and F_Y show a periodic behavior related to the milling process. However, the maximum and minimum values of both components show a gap associated to the reaction of the material to compression stress in Y.

Average values of the absolute records of the components have been used for studying the influence of the cutting parameters. Results obtained has allowed proposing marginal potential models $F_{X,Y,Z}$ (f_z) and $F_{Y,Z}(V)$. So, $F_{Y,Z}(f_z,V)$ responds to a combined potential model.

On the other hand, $F_X(V)$ is well adjusted to a parabolic model. Thus, a combined potential-parabolic model can be proposed for $F_X(f_z,V)$.

All the models have preseted a good adjustment to the experimental data.

Acknowledgements

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