MATEC Web of Conferences 45, 04011 (2016)
DOI: 10.1051/matecconf/20164504011

The Study of Cutting Conditions Effects on the Damping Process Using the Experimental Taguchi Method

Haikel Mejri[1], Ziyed Sahraoui[1] and Kamel Mehdi[1,2]

[1]URMSSDT, Engineering National High School of Tunis (ENSIT), University of Tunis (UT), 5 Avenue Taha Hussein P.B. 56 Bab Mnara 1008 Tunis, Tunisia
[2]Preparatory Institute for Engineering Studies El Manar (IPEIMa), University of Tunis EL Manar (UTM), PB. 24, 2092 Tunis, Tunisia

Abstract. This article focuses on determining the effects of cutting conditions and their interactions on the cutting process damping in the case of curvilinear milling. The tests were performed using a numerical model simulation that allows the prediction of cutting forces and damping. The effects and interactions are determined using the Taguchi experimental method. Analysis of variance (ANOVA) was performed to know the level of importance of the machining parameters on the cutting damping process. The results revealed that the Depth of cut A_p "**C**" and cutting speed V_c "**B**" have the most significant influence on the **Cxx** and **Cxy** process damping. The variations of tool diameter D "**A**" and clearance angle **α** have remarkable effects on the process damping **Cxx**. The "**BC**" interaction has the greatest effect on the process damping **Cxx** while the "**AC**" interaction has the greatest effect on the process damping **Cxy**.

1 Introduction

The comprehension of the various phenomena related to machining is necessary in order to propose models and methods which can predict the stability area. In most carried out researches, (which aims at the determination of the influence of the various cutting parameters), the researchers simplified or completely excluded the cutting process damping [1]. In fact, the experiments showed that for low cutting speeds, the cutting damping process is stable [2].

An important contribution on knowledge of the physical modeling of the cutting process was provided by Tlusty [3]. He showed with Ismail [4] that the cutting process damping affects the stability during the machining and it increases with the reduction of the cutting speed.

In 2012, Mehdi and Zghal [5] presented a numerical model allowing the prediction of cutting forces in peripheral milling process. They studied the effects of tool parameters (diameter, helix angle, number of teeth) on cutting process damping and cutting force distributions. In this model the cutting damping process was presented by the following matrix:

$$[C_c]=\begin{bmatrix} C_{xx}(t) & C_{xy}(t) \\ C_{yx}(t) & C_{yy}(t) \end{bmatrix}$$

Where:

$$C_{xx}(t)=\sum_{j=1}^{N_t}\sum_{k=1}^{N_d}\delta_{k,j}[c_{t_j}(t)+c_{r_j}(t)]\cos\varphi_j(t)\sin\varphi_j(t) \tag{1}$$

$$C_{xy}(t)=\sum_{j=1}^{N_t}\sum_{k=1}^{N_d}\delta_{k,j}[c_{t_j}(t)\cos^2\varphi_j(t)-c_{r_j}(t)\sin^2\varphi_j(t)] \tag{2}$$

$$C_{yx}(t)=\sum_{j=1}^{N_t}\sum_{k=1}^{N_d}\delta_{k,j}[c_{r_j}(t)\cos^2\varphi_j(t)-c_{t_j}(t)\sin^2\varphi_j(t)] \tag{3}$$

$$C_{yy}(t)=-C_{xx}(t) \tag{4}$$

Where:

$c_{r_j}(t)$ and $c_{t_j}(t)$ represent the cutting damping factors in the thrust and tangential directions,

$\varphi_j(t)$ is the position angle of a point on the cutting edge of the j^{th} helical flute,

N_t is the number of the tool's teeth and N_d is the number of the elementary cutting disks.

$\delta_{k,j}$ is equal to 1, if the j^{th} tooth of the elementary k^{th} disk of the tool is in cut, and 0 if it's out of cut.

It is difficult to determine the cutting process damping in experiments, hence the importance of the numerical model simulation which was presented and validated experimentally. This model allowed us, initially, to determine the cutting process damping while using the experimental cutting values. Secondly, it permitted to study the variation of the damping process in function of cutting parameters thus enhancing the results already presented by researchers over the years by using the experimental plans method. In 2015, Li Xin and all [6] confirmed the importance of taking into account the cutting dumping process in their research on the machining of thin-walled workpiece.

The experimental plans method, is applicable to all kinds of engineering problems [7-10], and it brings a rigorous approach in the governance and the establishment of the tests, which enables us not to reason more by groping.

This paper comes to complete the previous work of Mehdi and Zghal [5]. It focuses on determining the effects of cutting conditions and their interactions on the cutting process damping in the case of curvilinear milling. The tests were performed using a numerical model simulation that allows the prediction of cutting forces and damping. The effects and interactions are determined using the Taguchi experimental method. Analysis of variance (ANOVA) was performed to know the level of importance of the machining parameters on the cutting damping process.

2 Cutting process damping Cxx

In this part, we will use the parameters of cut for curvilinear machining allowed in table 1and the material properties in table 2.

Table 1. L16 standard table of settings applied to the simulation

N° test	D (A) (mm)	Vc (B) (m/min)	Ap (C) (mm)	α (D) (degrees)
1	6	25	0,25	4
2	6	25	0,25	15
3	6	25	3	4
4	6	25	3	15
5	6	300	0,25	4
6	6	300	0,25	15
7	6	300	3	4
8	6	300	3	15
9	40	25	0,25	4
10	40	25	0,25	15
11	40	25	3	4
12	40	25	3	15
13	40	300	0,25	4
14	40	300	0,25	15
15	40	300	3	4
16	40	300	3	15

Figure 1 presents the results obtained by simulation of cutting forces. During each test, the measurement of cutting damping process Cxx was taken into account and we made the average.

Table 2. Material properties

Steel	A60
Rr (MPa)	570
Re (MPa)	335
E (MPa)	200000
Density ρ (Kg/m3)	7850
Poisson's ratio	0.29

2.1 Calculation of average effects of factors and the interactions effect

The average value response of all factors of a jth level is given equation (5).

$$\overline{A}_j = \frac{1}{n}\sum_{i=1}^{n} R_{ij} \tag{5}$$

Here, we have considered two levels (j = 1, 2). Table 3 presents the average response to each factor level.

The overall average $\overline{T}$ of all the tests corresponds to the central point of average responses for the levels of each factor:

$$\overline{T} = \frac{\overline{A}1+\overline{A}2}{2} = \frac{210.961+159}{2} = 184.98\,Ns/m \tag{6}$$

The average effect of each factor level, appreciates relatively to the overall average. For example, the average effect of the factor A at the level 1 is calculated by the following equation:

$$E_{A_1} = \overline{A}1 - \overline{T} = 210.961 - 184.98 = 25.981\mu m \tag{7}$$

Similarly, we calculate the average effect of the A at the level 2:

$$E_{A_2} = \overline{A}2 - \overline{T} = 159 - 184.98 = -25.98\mu m \tag{8}$$

It is clear that: $EA_1 = -EA_2$

Table 4 gives the average effects of all factors.

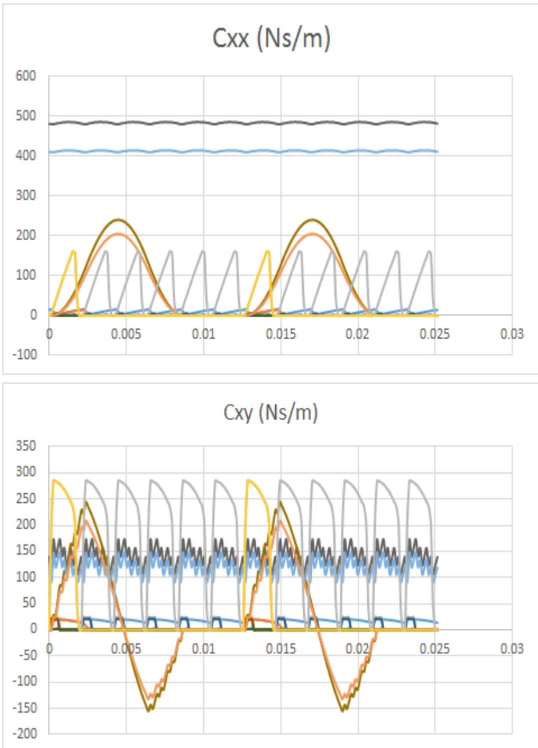

Figure 1. Effect of cutting parameters on cutting process damping (simulation)

Table 3. Average values of factors responses for each level

Fact	Average response for each factor level	
	Lev. 1	Lev. 2
A	210.961	159.000
B	266.469	103.493
C	50.438	319.524
D	151.689	218.273

Table 4. Effect factors on the measured values.

Fact	Effect of factors on the measured values	
	Lev. 1	Lev. 2
A	25.981	-25.981
B	81.488	-81.488
C	-134.543	134.543
D	-33.292	33.292

2.2 Calculation of the interactions

By applying the general formula of calculation of the interactions, we find for IA_1B_1:

$$I_{A_1B_1} = \overline{A}_1\overline{B}_1 - E_{A_1} - E_{B1} - \overline{T} \quad (9)$$

The average response related to each of the combinations AB is calculated using the same principle as for the following factors:

$$\overline{A}_1\overline{B}_1 = \frac{160.86+160.86+204.76+414.11}{4} = 235.148 \quad Ns/m \quad (10)$$

Table 5 gives the average values of the interactions

Table 5. Average values of interactions.

Average values of interactions			
A_1B_1	A_1B_2	A_2B_1	A_2B_2
235.148	186.775	297.790	20.210
A_1C_1	A_1C_2	A_2C_1	A_2C_2
85.905	336.018	14.970	303.030
A_1D_1	A_1D_2	A_2D_1	A_2D_2
153.166	283.071	149.250	168.750
B_1C_1	B_1C_2	B_2C_1	B_2C_2
73.092	493.309	51.642	187.243
B_1D_1	B_1D_2	B_2D_1	B_2D_2
230.550	302.388	72.828	134.158
C_1D_1	C_1D_2	C_2D_1	C_2D_2
50.438	34.663	252.940	386.108

Then, from this table, we get:

$$I_{A_1B_1} = 235.148 - 25.98 - 81.488 - 184.98 = -57.30\,\mu m \quad (11)$$

And in the same way we calculate the other interactions. The values of these interactions are given in table 6.

Table 6. Effect of interactions on the measured values

Effect of interactions on the measured values			
A_1B_1	A_1B_2	A_2B_1	A_2B_2
-57.302	57.302	57.302	-57.302
A_1C_1	A_1C_2	A_2C_1	A_2C_2
9.487	-9.487	-9.487	9.487
A_1D_1	A_1D_2	A_2D_1	A_2D_2
-24.504	-0.005	23.542	-23.542
B_1C_1	B_1C_2	B_2C_1	B_2C_2
-58.834	92.297	82.692	-50.793
B_1D_1	B_1D_2	B_2D_1	B_2D_2
-2.627	2.627	2.627	-2.627
C_1D_1	C_1D_2	C_2D_1	C_2D_2
33.292	-0.025	-33.292	33.292

2.3 Discussion

The curves illustrated in figures 2 and 3 represent all the effects and interactions on the cutting damping process Cxx. From these figures, we can see that:

-The pass depth (C) and the cutting speed (B) have the most significant influence on the process damping Cxx. Indeed, if we increase the cutting speed, the process damping Cxx decrease.

-By against, if we increase the depth of cutting, the process damping Cxx increase.

-The variation of the tool diameter (D) and the variation of the clearance angle (α) have an effect on cutting damping process Cxx. However, the effect of both factors remains lowers than that the depth of cutting and cutting speed.

-The BC interaction has the greatest effect on the cutting damping process Cxx, AB interaction also exhibits a significant effect. This is a reason for which it must be taken into consideration.

-The CD interaction is intense, although its effect is lower than that of BC and AB.

-Interactions AB, AC, AD and BC are low.

-The BD interaction is null, then it has no effect on the cutting damping process Cxx.

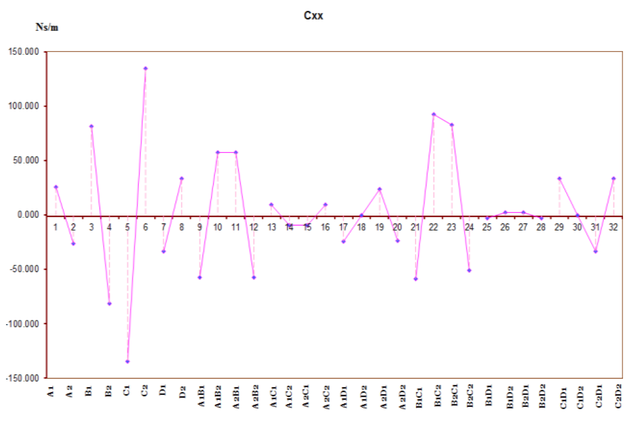

Figure 2. Effect of factors and interactions on Cxx

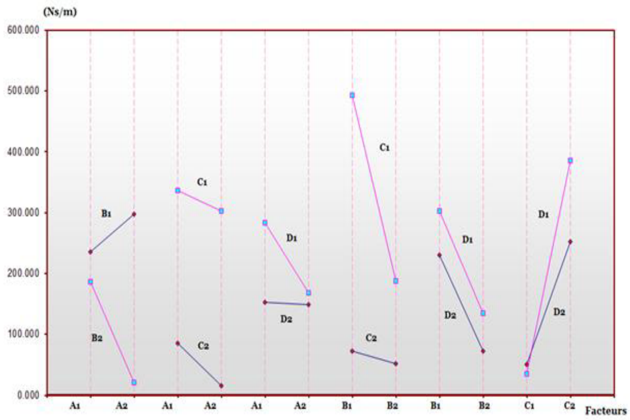

Figure 3. Effect of interactions on Cxx cutting damping

3 Cutting process damping Cxy

Like in the case of cutting process damping Cxx, the same approach has been adopted to determine the tables of the average response, the effect of factors on the measured values, the average values of the interactions and the effect of the interactions on the measured values (tables 7, 8, 9 and 10).

Table 7. Average values of factors responses for each level.

Fact	Average values of factors for each level	
	Lev. 1	Lev. 2
A	168.333	140.233
B	244.599	63.967
C	82.679	225.886
D	152.224	156.342

Table 8. Effect of factors on the measured values.

Fact	Effect of factors on the measured values	
	Lev,1	Lev,2
A	14.050	-14.050
B	90.316	-90.316
C	-71.604	71.604
D	-2.059	2.059

Table 9. Average values of interactions

Average values of interactions			
A_1B_1	A_1B_2	A_2B_1	A_2B_2
231.560	105.106	257.638	22.828
A_1C_1	A_1C_2	A_2C_1	A_2C_2
143.341	193.325	22.018	258.448
A1D1	A_1D_2	A_2D_1	A_2D_2
184.883	151.783	119.565	160.900
B1C1	B_1C_2	B_2C_1	B_2C_2
152.638	336.560	12.721	115.213
B1D1	B_1D_2	B_2D_1	B_2D_2
231.945	257.253	72.503	55.431
C_1D_1	C_1D_2	C_2D_1	C_2D_2
82.678	82.681	221.770	230.003

Table 10. Effect of the interactions on the measured values

Effect of the interactions on the measured value			
A_1B_1	A_1B_2	A_2B_1	A_2B_2
-27.089	27.089	27.089	-27.089
A_1C_1	A_1C_2	A_2C_1	A_2C_2
46.612	-46.612	-46.612	46.612
A1D1	A_1D_2	A_2D_1	A_2D_2
18.609	-18.609	-18.609	18.609
B1C1	B_1C_2	B_2C_1	B_2C_2
-20.358	20.358	20.358	-20.358
B1D1	B_1D_2	B_2D_1	B_2D_2
-10.595	10.595	10.595	-10.595
C_1D_1	C_1D_2	C_2D_1	C_2D_2
2.058	-2.057	-2.058	2.058

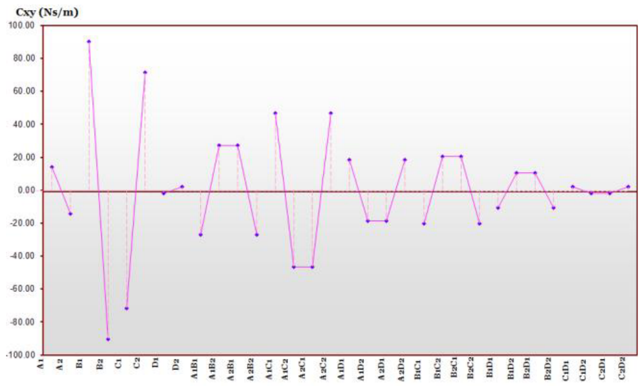

Figure 4. Effect of factors and interactions on Cxy

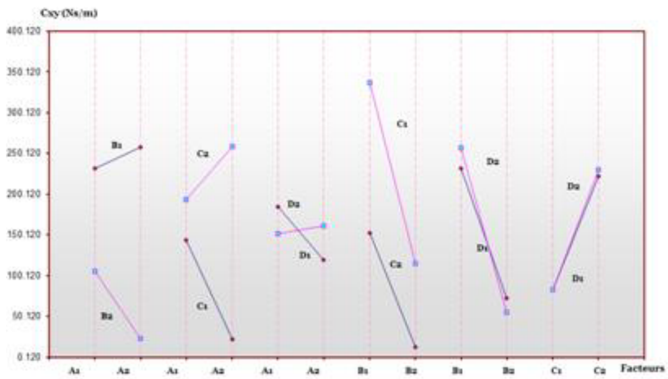

Figure 5. Effect of interactions on Cxy damping

The curves illustrated in figures 4 and 5 represent all the effects and interactions on the Cxy cutting damping process. From these figures we can see that:

-The cutting depth (C) and the cutting speed (B) have the most significant influence on the cutting damping process Cxy. In fact if we increase the cutting speed, the cutting damping process Cxy decrease. On the other hand, if we increase the depth of cut, the cutting damping process Cxy increase. It is noticed that the effect of the cutting speed (B) is more important.

-The cutting damping process Cxy passes by negative values by increasing the cutting depth.

-The interaction AC has the greatest effect on the cutting damping process Cxy, interactions AB, AD and BC also present a significant effect.

-The interactions AD, BD and CD are intense; despite their effects remain lower than that of AC.

-Interactions AB, AC and BC are not very significant.

4 Conclusions

In this paper, a Taguchi experimental plan was used. This method allows the limitation of the number of necessary and sufficient tests to study the cutting damping process in curvilinear milling was used.

We have succeeded in identify the main influential machining parameters on the cutting damping process. Such as the tool diameter (D), the cutting depth (ap), the cutting speed (Vc) and clearance angle (α).

The simulation results have allowed us to conclude that:

-The cutting depth (C) and the cutting speed (B) have the most significant influence on the cutting damping process Cxx and Cxy.

-The variation of the tool diameter (D) and the variation of the clearance angle (α) act in a remarkable manner on the cutting damping process Cxx, but they have a less significant effect on the cutting damping process Cxy.

-The BC interaction has the greatest effect on the cutting damping process Cxx, the AB interaction of same has a significant effect.

-AC interaction has the greatest effect on the cutting damping process Cxy, interactions AB, AD and BC of same have a significant effect. This is one reason why we must take into consideration.

Finally, it is important to insist on the major role of numerical model simulation, with it we have predicted the cutting damping process in curvilinear milling. The future work of this research is the study of the effect of cutting parameters and tool parameters and their interactions on the cutting forces.

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