SELECTION OF MACHINING CONDITIONS FOR AERONAUTIC COMPOSITE USING VIBRATION ANALYSIS

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1 Abstract

The constant increase of the composite part constitutes a priority for the aeronautic industry. However, the machining step of this material is complicated by different phenomena: delamination, burned resin and cutting edge chipping. The objective of the current study is to characterize the cutting conditions using vibration analysis in order to avoid the defects (stated above). Down milling tests operation was performed in a high speed milling machine (PCI Meteor 10) on a composite material carbon/epoxy (T800S/M21), while milling cutter of diameter 80mm equipped with a single PCD insert. In the experimental evaluation, a central composite design with 20 combinations were studied using parameters; cutting speed , depth of cut and feed per revolution , and the vibration levels were measured for each case. Methods such as Multiple Linear Regression (MLR) and Response Surface Methodology (RSM) were used to create mathematical models using the experimental data.

2 Introduction

The machining conditions play an important role in determining lifespan and mechanical resistance of a material [1-4].
Many studies have shown that the cutting conditions, the material heterogeneity and the formation of these materials not only generate a premature cutting tools wear [5], but also severe damage to the work-piece [6]. The most common defects encountered during the machining of composites are delamination, tearing of fibers, the debonding and degradation of thermal origin. In order to understand their appearance, some authors have linked the cutting conditions to damage [7] and mechanical properties of the machined product. Koplev et al [8] and Ramulu et al [9] showed that the orientation of the folds relative to the cutting edge has a large influence on the generation of defects in the composite.

Characterization of the machining quality by analysis the surface roughness is very sensitive, and the measurement error is important because of the orientation of fibers composite.

The aim of this work is to present a new technique for selecting cutting conditions by the analysis of both vibration and defects generation during machining of a composite material.

The results shows that surface defects and wear in the cutting tool started to appear before a threshold of vibration. It was also analysed that the interaction between feed per revolution and depth of cut was the most influential factor in the mathematical model. The variance analysis (ANOVA) was used to approve the model.

3 Response surface methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques useful for analyzing problems in which several independent variables influence a dependent variable or response. The goal is to optimize the response [10]. In many experimental conditions, the independent factors as given in Eq. (1) Then theses factors can have a functional relationship or response as follows:

$$Y = \mathbf{\Phi}(x_1, x_2, ..., x_n) \pm e_r \tag{1}$$

Between the response Y and x_1, x_2,..., x_n of n quantitative factors, the function $\mathbf{\Phi}$ is called response surface or response function. The experimental error is represented by e_r.

For a given set of independent variables, a characteristic surface is responded. When the mathematical form of $\mathbf{\Phi}$ is unknown, it can be approximate by a statistical methods using polynomial functions.

In the present investigation, RSM has been applied for developing the mathematical model. In applying the response surface methodology, a mathematical model is fitted on the independent variable response surface.

The second order polynomial (regression) equation used to represent the response surface Y is given by [11].

$$Y = b_0 + \sum_{i=1}^{n} \mathbf{b_i x_i} + \sum_{i=1}^{n} \mathbf{b_{ii} x_i}^2 + \sum_{i \prec j}^{n} \mathbf{b_{ij} x_i x_j} + r_e \tag{2}$$

Where b_0 represents the linear effect of $\boldsymbol{x_i}$, $\boldsymbol{b_{ii}}$ represents the quadratic effect of $\boldsymbol{x_i}$ and $\boldsymbol{b_{ij}}$ reveals the linear-by-linear interaction between $\boldsymbol{x_i}$ and $\boldsymbol{x_j}$.

In order to estimate the regression coefficients, a several experimental design plan are available.

4 Experimental details

Down milling tests operation were performed in a high speed milling machine, (PCI Meteor 10) on a composite material carbon/epoxy, T800S/M21 while milling cutter of diameter 80mm equipped with a single PCD insert.

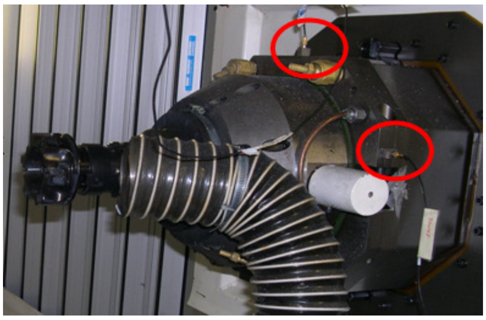

Fig. 1.Cutting tool

3.1 Design of experiment:

In the experimentation, a central composite design plan with 20 combinations were studied using the parameters; cutting speed *(Vc)*, depth of cut *(ap)* and feed per revolution *(f)*, and the vibration levels (in the three directions i.e. x, y and z) were measured for each case.The three independent parameters *ap*, *f*, and *Vc* have been chosen in accordance with the recommendations provided by the manufacturer of cutting tools SAFETY [12].

The upper limit of a factor was coded as +1.68, and the lower limit as –1.68.

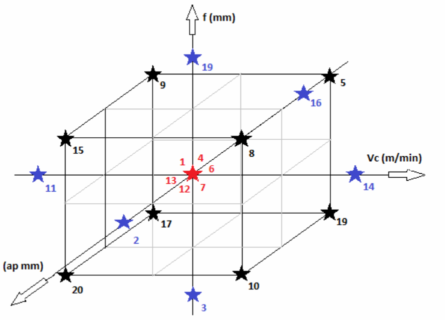

Fig. 2. Central composite design

Multiple Linear Regression Method and RSM were used to create mathematical models using the experimental data.

The experiment variables are summarized in table 1.

Table 1. Input parameters

Codified variables	*Vc* (m/min)	*f* (mm)	*ap* (mm)
Min (-1.68)	659	0.032	0.660
Min (-1)	1000	0.100	1.000
Mean (0)	1500	0.200	1.500
Max (+1)	2000	0.300	2.000
Max (+1.68)	2349	0.368	2.340

3.2 Vibration measurement

Vibrations are measured by a tri-axial accelerometer mounted on the work-piece (Fig.3).A multi-analyzer (Brüel and Kjær 3560) connected to a computer for recording temporal data using the software Pulse Labshop.

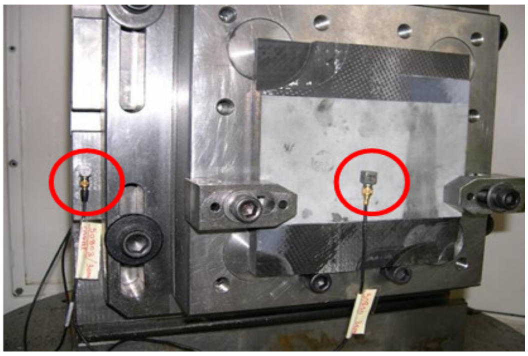

Fig. 3.Tri-axial accelerometer

Root mean square (RMS) acceleration was calculated on the whole signal. To take fiber orientation of composite into account, the root square of the rms vibration measured on the 3 directions x, y and z was computed as shown:

$$A_{rms} = \sqrt{Ax_{rms}^{\;2} + Ay_{rms}^{\;2} + Az_{rms}^{\;2}} \qquad (3)$$

3.3 Analysis of machining defects composites

Delamination is one of the most dangerous defects in machining composite (Fig. 4, 5, 6). The stiffness loss may decrease the life of a composite structure significantly.

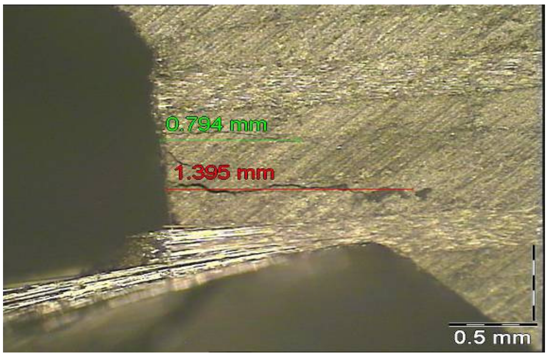

Fig. 4. Delamination (test 2)

To use the full capacity of composites, it is necessary to analyze the initiation and growth of delamination.

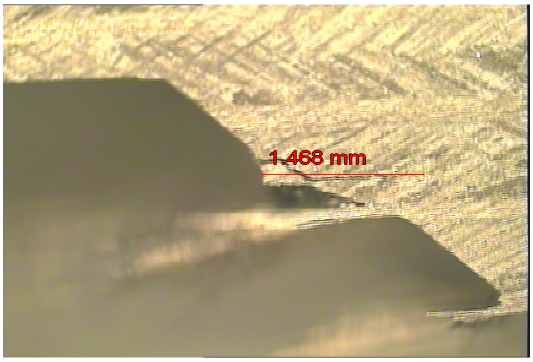

Fig. 5 Delamination (test 19)

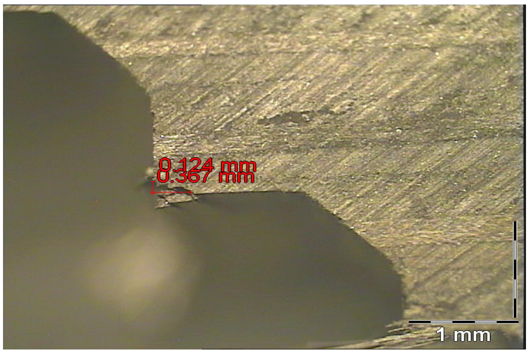

Fig. 6. Delamination (test 15)

Other defects such as wear of cutting tool (Fig.6) and the overheat of the composite matrix (Fig.7) may appear during the machining of composites.

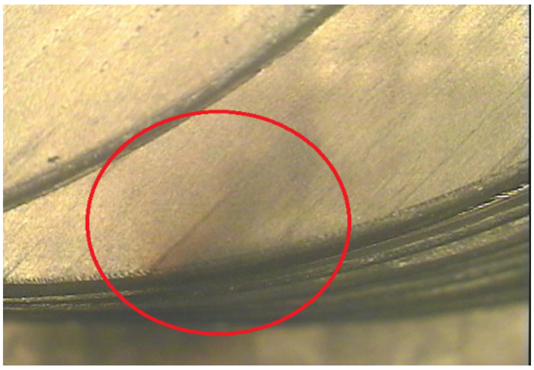

Fig. 7. Heating of the composite (test 15)

Table 2, summarizes all the defects found during testing.

Table 2. Summary table of measures

N°	Vc	f	ap	A_{rms}	Defects
1	1500	0.2	1.5	129.56	
2	1500	0.2	2.34	232.78	Delamination
3	1500	0.032	1.5	56.14	
4	1500	0.2	1.5	142.24	
5	2000	0.3	1	124.07	
6	1500	0.2	1.5	128.50	
7	1500	0.2	1.5	162.47	
8	2000	0.3	2	279.54	Tool wear+ delamination
9	1000	0.3	1	124.84	
10	2000	0.1	2	122.05	
11	659	0.2	1.5	128.11	
12	1500	0.2	1.5	127.97	
13	1500	0.2	1.5	150.47	
14	2340	0.2	1.5	157.91	
15	1000	0.3	2	214.77	Tool wear+ Heating
16	1500	0.2	0.66	78.51	
17	1000	0.1	1	47.34	
18	2000	0.1	1	65.34	
19	1500	0.368	1.5	241.17	delamination
20	1000	0.1	2	108.23	

5 Results and discussion

Three effects are discussed by the model such as linear, interactions and quadratic.

$$\begin{aligned} A_{rms} = {} & 62.185 - 0.018\times Vc - 80.999\times f - 49.112\times ap \\ & + 5.368\times f^2 + 10.124\times ap^2 + 46.255\times ap\times f \\ & + 0.080\times Vc\times f + 0.031\times Vc\times ap + 319.541\times f\times ap \end{aligned} \quad (4)$$

Regression factors linked to this model helps us to build the relation between the work-piece vibration and the three study parameters:

The coefficient of determination equals to 0.962, in others terms, 96.2% of the vibration variations fits to the model and 3.8% of them can't be explained. The model is better if this coefficient approaches the value of 1. This coefficient indicates that the vibrations measurements satisfy the model used.

In order to test the model significance, the variance has been calculated and is given in tab.3. Fisher test shows us that the F-probability is lower than 0.001 (Prob>F), this results indicate us that the independent variable give enough informations to the model, this conclusion can be affirm with 0.1% of risk.

The variance proportion of the dependant variable which fits to the model is 33.06 time higher than the variance proportion of the dependant variable which can't be explained.

On the other hand, we can noticed that in this model, only interaction effects are significant (Prob> F is less than 0.05, or 5 %.)

Table 3. ANOVA

Source	DDL	SCE	SS	F	Prob > F
Regression	9	69792.10	7754.67	33.06	<0.001
Linear	3	66988.10	48.59	0.21	0.889
Quadratic	3	161.60	53.85	0.23	0.874
Interaction	3	2642.40	880.80	3.76	0.048
Residual	5	1005.60			
Total	19	72137.60			

Table 4. Model parameters

Source	Value	Ecart-type	F	P-Value
Constant	62.185	87.813	0.708	0.495
Vc	-0.018	0.063	-0.279	0.786
f	-80.999	283.937	-0.285	0.781
Ap	-49.112	62.807	-0.782	0.452
$Vc\times Vc$	-0.000	0.000	-0.480	0.642
$f\times f$	5.368	404.092	0.013	0.990
$ap\times ap$	10.124	16.164	0.626	0.545
$Vc\times f$	0.080	0.108	0.743	0.475
$Vc\times ap$	0.031	0.022	1.417	0.187
$f\times ap$	319.541	108.294	2.951	0.015

Table 4 shows that among all combinations, the interaction between feed rate and depth of cut was the most influential factor in the mathematical model. For this interaction, the P-value equal to 0.015 which is less than 0.05. This means that there are 1.5 chances in 100 that the true value of the coefficient of interaction $f \times ap$ is zero.

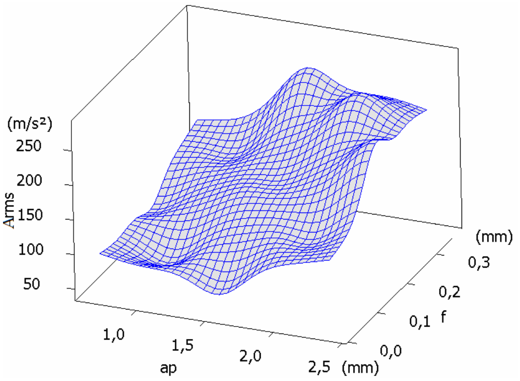

Fig. 8. 3D surface graph for vibration A_{rms} at Vc=1500 m/min as *f* and *ap* varies.

Fig. 8 gives the 3D surface graph for A_{rms} vibrations at *Vc*=1500 m/min as feed rate and depth of cut varies. It is clear that vibration increases with increase in feed rate and depth of cut. More *f* and *ap* increases, more A_{rms} vibration increase.

The results shows that in the test 2, 8, 15 and 19, defects such as delamination and epoxy overheating were observed and cutting tool wear started to appear before the value of A_{rms} vibration of 175 m/s². To limit the occurrence of these defects, A_{rms} vibration threshold of 175 m/s² was set (Fig.9).

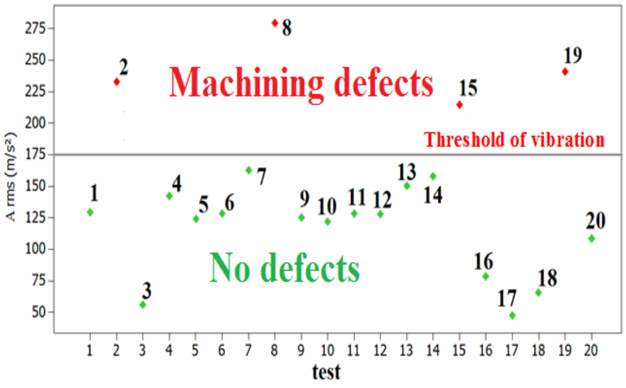

Fig. 9. Threshold of vibration

From the mathematical model of the A_{rms} vibration and threshold of vibration that eliminates the appearing defects, region with defects have been defined. These regions can help the operator to making a choice for cutting parameters (cutting speed, depth of cut and feed rate) in order to avoid defects while machining.

For *Vc*=1500 m/min (Fig.10), depending on *ap* chosen, we obtains the value of *f* . For example for *ap*=2 mm, the value of *f* must be less than 0.17 mm.

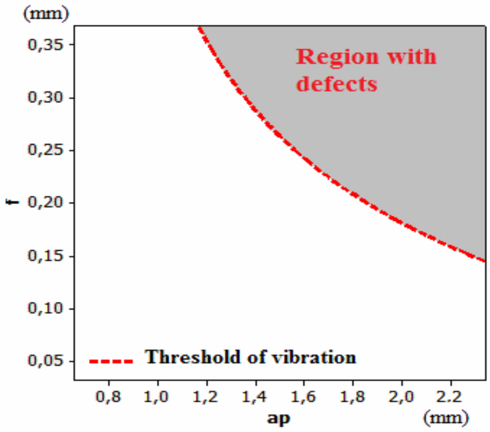

Fig. 10. Selection of *f* and *ap* while *Vc*=1500 m/min

For *f*=0.2 mm (Fig.11), depending on the *Vc* chosen, we obtains the value of *ap*, eg for *Vc*=1500 m/min, *ap* must be less than 1.8 mm.

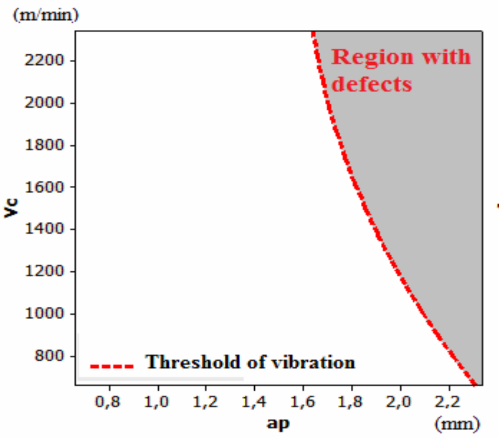

Fig. 11. Selection of *Vc* and *ap* while *f* =0.2 mm

For *ap*=1.5 mm (Fig.12), depending on the chosen value of *Vc* , we obtains the value of *f*, eg *Vc*=1500 m/min, *f* must be less than 0.27 mm.

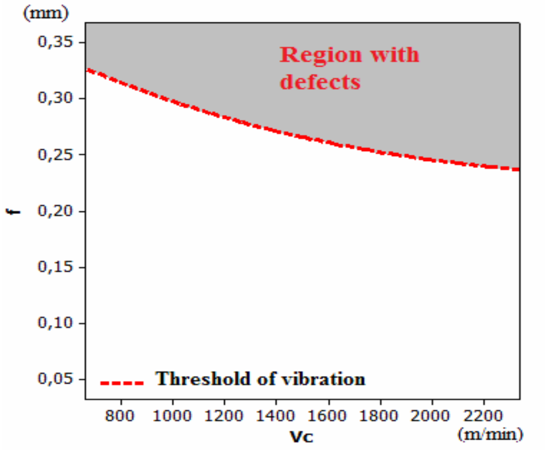

Fig. 12. Selection of *Vc* and *f* while *ap*=0.2 mm

In order to verify the accuracy of the model developed, confirmation experiment was performed. The test condition for the confirmation test was so chosen that they be within the range of the levels defined previously (*Vc*=1500 m/min, *ap*=1.5 mm and *f*=(0.1, 0.2, 0.3, 0.35 mm). Test show that the response equation for the A_{rms} vibration evolved through RSM can be used to successfully predict the defects for any combination of the feed rate, cutting speed and depth of cut within the range of the experimentation conducted.

6 Conclusions

This study is a combination of several methods for detecting machining defects which can appear on a composite material carbon/epoxy. Vibration analysis of the work-piece for each cutting condition is used; a threshold of vibration is defined from the observations of the piece according to the machining defects. The defects studied in this study are: delamination of the composite layer, overheat of the composite matrix and the wear of the cutting tool wear. The response surface methodology was used to determine the Analytical model which expresses the level of vibration according to the three cutting parameters cutting speed *Vc*, depth of cut *ap* and feed per revolution *f*. The ANOVA results approved that the mathematical models used in this study could adequately describe the performance indicators within the limits of the factors that are being investigated with 95% confidence interval. The analysis results show that the RMS vibrations are only influenced by the interaction of feed rate /depth of cut.

This study should help the operator to choice the cutting parameters such as cutting speed, depth of cut and feed per revolution in order to avoid damage of the composite material carbon/epoxy, T800S/M21, and the cutting tool while machining, using vibration analysis.

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