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Procedia CIRP 77 (2018) 307–310

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

Effect of curing pressure on machinability of carbon fiber composite

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Abstract

The increasing use of composite materials in aerospace structures and their associated manufacturing and machining processes have shown the need to reengineer traditional tools. This study aims to provide an understanding of the relationship between the manufacturing parameters of carbon fiber/epoxy composites and their machinability. The main objective is to establish a new predictive model for cutting forces during machining as a function of curing pressure, cutting speed and feed rate. The research methodology is based on a multifactorial design of experiments, with input factors being the curing pressure, the feed rate, and the cutting speed. To examine the effect of the composite curing pressure, correlations between the curing pressure and the void content, as well as between the curing pressure and the mechanical properties, are evaluated. The cutting forces are then predicted based on the curing pressure and the cutting parameters.

Keywords: fiber reinforced plastic; curing pressure; void content; mechanical properties; trimming

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1. Introduction

The aerospace industry tends to design and manufacture increasingly larger and lighter aircrafts with the use of new materials such as carbon fiber composites. Thanks to their manufacturing methods, composites are produced close to their final shape, but finishing operations in machining remain necessary. Several researchers have conducted experiments and developed models allowing the prediction of composite machinability and parameters such as the cutting forces, tool life and surface integrity. During carbon fiber reinforced polymers (CFRP) end-milling, a low feed rate and a high cutting speed were found preferable for generating a high quality surface finish which has different cutting mechanisms for each ply orientation [1]. Chatelain et al. characterized the surface texture through profile roughness parameters for each ply orientation (0°, ±45° and 90°) [2]. The cutting tool geometry, as well as the machining parameters are among the variables that directly influence the cutting force magnitude and the part quality such as roughness parameters [3].

Mathematical model allowing the prediction of cutting forces based on machining experiments on unidirectional CFRP laminates [4]. Bérubé and Zaghbani et al. considered quasi-isotropic CFRP laminates with varying thicknesses and established mathematical models combining input parameters (such as the feed rate, cutting speed and laminate thickness) [5-6]. Most studies have led to similar conclusions regarding the input parameters, i.e., the fiber orientation, the feed rate, and the cutting speed mainly influence the cutting forces. However, current models have limitations in predicting cutting forces with a high confidence level. To improve mathematical models, several possibilities can be considered, such as combining all known influential parameters into a single study or looking for significant parameters that are yet to be fully developed in the literature. Among these, the pressure used during the manufacturing process may be of interest since it is directly related to the laminate void content. Olivier et al.

10.1016/j.procir.2018.09.022

showed that a low composite curing pressure leads to a high void content with an exponential decrease in the void content with a curing pressure increase after the manufacture of $[0]_{16}$ CFRP laminates [7].

The mechanical properties of composites affected by the void content also constitute an important research subject. For instance, Ghiorse highlighted the relationship between the void content and the InterLaminar Shear Strength (ILSS) for CFRP [8]. To relate the mechanical properties of the composites to their machining, the trimming of carbon fiber/epoxy laminates was used to highlight the relationship between the ILSS and the cutting forces. However, no research has thus far been identified relating the curing pressure and the void content to its machinability, which is the aim of this communication.

Herein, an experimental approach is proposed to validate the impact of the curing pressure on the void content. Models are developed to estimate the cutting forces, and the proposed models are based on the combined effect of the cutting parameters (feed rate and cutting speed) and the curing pressure.

2. Methodology

2.1. CFRP laminates manufacturing

Laminates were manufactured using sixteen plain weave fabric pre-impregnated carbon fiber/epoxy plies. The laminate stacking sequence was $[90/45/90/45/90/45_3]_S$. Two CFRP plates (25 x 24 cm) were manufactured for each pressure, using an autoclave. The same vacuum pressure P_{vac} which is the pressure in the vacuum bag, and the same temperature cycles were applied in all cases (Fig. 1). The weight fiber content before curing was 63.0 ± 3.0%, according to the supplier specifications. The tests were performed for five curing pressures P (pressure in the autoclave): 0.270, 0.410, 0.550, 0.720 and 0.860 MPa.

2.2. Void content estimation

The porosity was estimated in two 10 x 2 cm samples for each curing pressure value. Samples were cut and their cross-sections were polished, and then observed through an optical microscope. Fifteen sample pictures of a 3 x 4 mm section were taken for each sample. An image analysis software was used to evaluate the void content of the material, based on the following equation:

$$V_V \approx \frac{1}{n}\sum_{i=1}^{n}\frac{S^i_{voids}}{S^i_{picture}} \qquad (1)$$

where:
S^i_{voids}: total voids area over the picture (mm²)
$S^i_{picture}$: total picture area (mm²)
n: number of picture samples with same characteristics

2.3. Trimming

The CFRP plates were machined using three cutting speeds (V_C: 300, 425 and 550 m/min) and three feed rates (f: 0.2032, 0.254 and 0.3048 mm/rev), giving a total of nine different sets of cutting parameters for the squared plan of experiment of machining conditions. The tests were repeated three times for the four corner points of the plan of experiment and twice for the rest in order to reduce measurement errors and dispersion effects. Thus, twenty-two coupons were machined for each of the five curing pressures. The cutting tool and machining conditions were selected following Bérubé's recommendations [5]. The cutting tool was a two-flute polycrystalline diamond (PCD) end mill with a diameter of 9.525 mm (Fig. 2). The trimming was performed in full tool engagement under dry conditions, using the Huron K2XFive CNC machine. To characterize the machinability, three cutting force signals were acquired at a 12 kHz frequency rate for all 110 routing passes, using a Kistler 9255B dynamometer table (Fig. 2). The feed force F_f, the normal force F_n and the axial force F_z signals were recorded as for each 40 mm pass length.

The tool wear impact on cutting forces was considered non-significant. This last assumption was justified by the cutting length, which was short compared to the total length of cut during the whole tool life [9]. In addition, the tool wear was regularly evaluated to validate the quasi-static state of the tool wear.

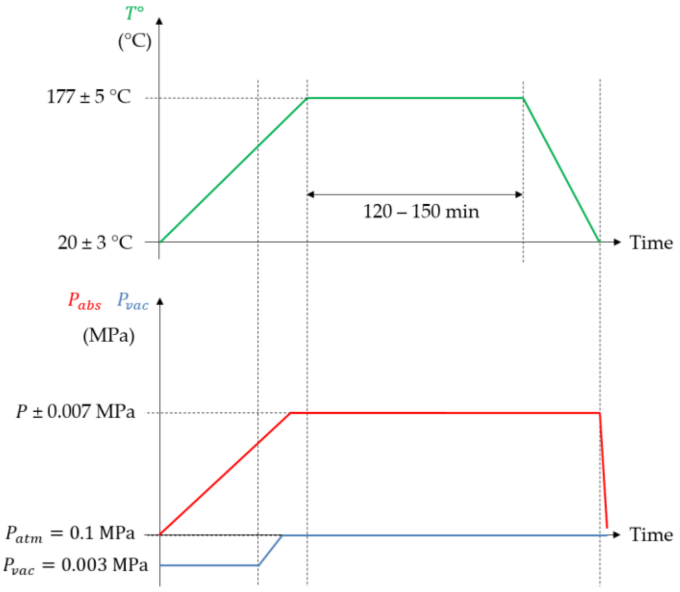

Fig. 1. Temperature and pressures applied during the CFRP curing cycle (P_{atm} is the atmospheric pressure)

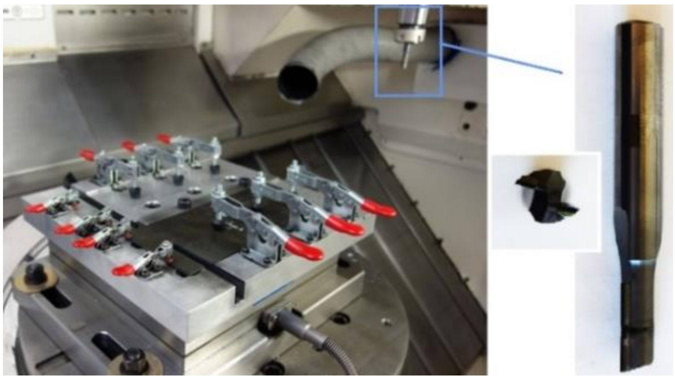

Fig. 2. Trimming set-up (left) and end-mill tool (right)

3. Results and discussion

A relationship between the void content and the curing pressure was first identified. An analysis of variance was performed to quantify the impact of the input parameters (curing pressure, cutting feed and speed) on the cutting forces. The composite machinability was considered through the cutting forces (feed, normal and axial forces). A model was proposed for each cutting force.

3.1. Void content

The curing pressure may influence the laminate fiber content as more resin is likely to be squeezed out at high pressures. The void content also tends to decrease with increasing curing pressure. Fig. 3 shows the void content estimated for the coupons manufactured under each curing pressure. As expected, the void content decreases when the curing pressure is increased up to 0.5 MPa. Above this value, the void content remains stable at around 0.1%. A linear relationship between the curing pressure and void content is observed for both areas (Fig. 3). It should be noted that the void content is always below 1.0%, which is an indication of relatively good laminate quality in all cases.

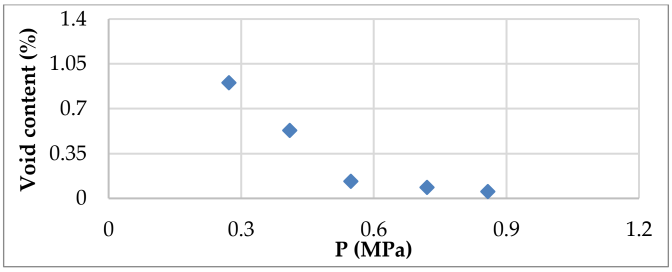

Fig. 3. Void content vs the curing pressure with linear models for different pressure ranges

3.2. Cutting forces analysis

The results of the cutting forces F_f and F_n are depicted in Fig. 4 and Fig. 5, respectively. The feed force F_f is influenced by the three input parameters: the cutting speed and feed and the curing pressure. The highest cutting forces are measured for higher curing pressure and cutting speed and feed. The normal force F_n appears to be impacted only by the cutting feed and the curing pressure.

The feed and normal forces are influenced by the curing pressure on the results mean and deviation as well. A higher curing pressure leads to higher feed and normal cutting forces but brings a reduction of the cutting force deviation. Still regarding the results deviation, the feed seems to have an influence on the results. In this case, the acquisition system frequency rate is not the cause because the cutting speed impact on the result deviation is not significant. Thus, lower cutting force deviations are found for high curing pressures and low feed rates.

The results of the normal cutting force F_n reach a stabilized limit for a curing pressure of around 0.5 MPa. No limit achieved is observable on the selected curing pressure range for the results of the feed force F_f.

The results of the axial cutting force F_z are depicted in Fig. 6. No particular trend can be observed since the input parameters show no influence on the axial cutting force. However, the deviation seems greater with the increase in the feed rate.

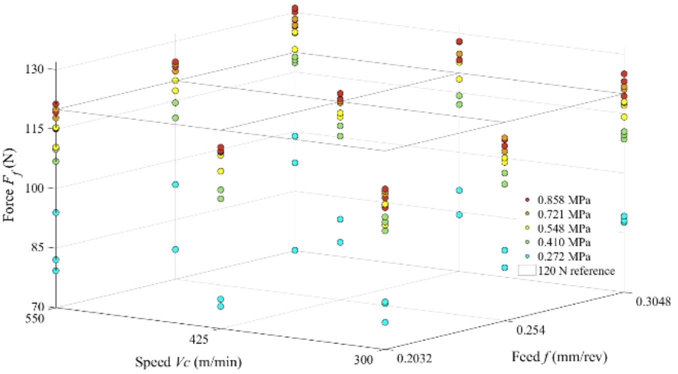

Fig. 4. Cutting forces F_f results plotted vs the feed, speed and cutting pressure

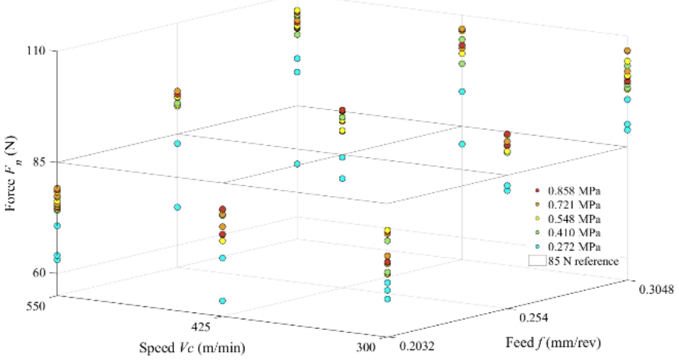

Fig. 5. Cutting forces F_n results plotted vs the feed, speed and cutting pressure

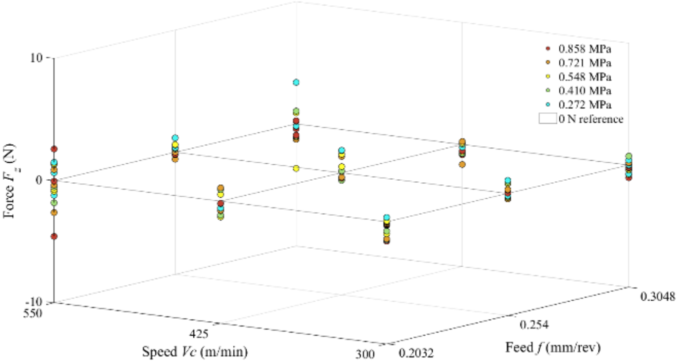

Fig. 6. Cutting forces F_z results vs the feed, speed and cutting pressure

This section aims to identify the parameters (f, V_C and P) influencing the cutting forces. A multivariate ANOVA was processed and optimized with the influential input parameters for each cutting force, F_f, F_n and F_z. Table 1 gives the optimized MANOVA for the data of each cutting force type. Same conclusions are obtained for the observations of the results for the feed and normal force. The axial cutting force F_z is only impacted by the feed but this influence remains limited.

The total cutting force is influenced by the three input parameters and by the interaction of the cutting feed and speed as well. The curing pressure is the least influential parameter for the total force. This pressure is certainly not significant for the axial force, but it strongly affects the feed and normal force. The curing pressure should have a strong influence on the total force as well. Any opposite results observed may be due to the axial cutting force.

Table 1. MANOVA optimized results for the cutting forces

	Source	Sum Sq.	d.f.	Mean Sq.	F	Prob>F
F_f	Feed	1917.5	2	958.8	69.7	0
	Speed	967.7	2	483.8	35.1	0
	Pressure	18448.3	4	4612	335	0
	Error	1390.7	101	13.77		
	Total	22726	109			
F_n	Feed	14809.7	2	7405	575	0
	Pressure	2753.9	4	688.5	53.5	0
	Error	1326	103	12.88		
	Total	18889.7	109			
F_z	Feed	9.6	2	4.817	4.62	0.0119
	Error	111.5	107	1.042		
	Total	121.1	109			

Due to the non-linearity of the cutting force vs the curing pressure, an input parameter substitution is performed before the modeling for the pressure. The selected replacement is based on the double-inverse function:

$$P' = \frac{1}{1+\frac{a}{P}} \qquad (2)$$

where:

P': substituted curing pressure (MPa)

a: substitution coefficient

Table 2 depicts the function coefficient values of the pressure substitution in order to linearize the cutting force response from the curing pressure variation.

Table 2. Input parameter substitution for the curing pressure

Coefficient	F_f	F_n
a	-0.1810	-0.2394

The statistical analysis presented includes first- and second-degree input interactions; for example, f^2 or $V_C \cdot f$ were considered. On the one hand, the second-degree polynomial is enough to characterize the relationship between the feed rate and the curing pressure and between the cutting speed and the curing pressure due to a level number of cutting feeds and speeds. Therefore, it is not necessary to carry out a cutting speed and feed rate substitution. On the other hand, a substitution is performed as described in the equation (2), where the coefficient values are presented in Table 2.

For each cutting force, models were built based on the MANOVA results in order to estimate the influencing parameters. The following equations give the optimized model functions for the cutting forces F_f and F_n respectively:

$$F_f = 109.96 + 2.770 \cdot 10^{-2} \cdot V_c + 96.09 \cdot f - 20.56 \cdot \frac{1}{1-\frac{0.1810}{P}} \qquad (3)$$

$$F_n = -57.51 + 942.6 \cdot f - 1.908 \cdot \frac{1}{1-\frac{0.2394}{P}} - 1333 \cdot f^2 \qquad (4)$$

For the cutting force models, all the second-degree possible interactions were evaluated, and the previous show only the interactions impacting each model, while other interactions were rejected due to their too low contributions.

4. Conclusion

The curing pressure is a major criterion for CFRP manufacturing. In this study, the impact of this pressure was evaluated vs the machinability. The machinability of the different curing pressure composites was evaluated through the cutting forces. The relationship between the manufacturing parameters of quasi-isotropic carbon fiber/epoxy laminates and their machinability was demonstrated.

First, the correlation between the curing pressure and the void content was confirmed. A double-inverse model was used to characterize the impact of the curing pressure on the cutting forces, in order to propose innovative cutting force models through machining experiments. These models, based on a multifactorial design of experiments, led to the development of a model for each of the feed, normal, axial forces. The feed and normal force were found to have a particularly good correlation with the influential parameters: feed rate (f and f^2), cutting speed (V_C), linear spindle speed ($V_C \cdot f$) and curing pressure (P). The proposed models for the cutting forces during machining provide significant advantages for manufacturers, including the appropriate selection of cutting parameters.

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