EFFECT OF VACUUM PRESSURE DURING CURING OF CARBON FIBRE LAMINATES ON THEIR MACHINABILITY

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Keywords: composites, trimming, curing pressure, machining

1 Introduction
The need to reduce the weight of structures has led to an increasing use of composite materials in the aerospace industry. One advantage that composites can provide is the reduction of component count number through higher integration. This is achieved thanks to their near net shape manufacturing ability, which allows them to be produced in complex shapes and large sizes. For functional or assembly requirements, many composite components still need to be finished with high accuracy, using various material removal processes; among the latter, drilling and trimming processes are often used to produce holes and cut-outs as well as accurate edge finishing. To improve the quality of parts finished using machining techniques, it is essential to have an adequate knowledge of the machinability of composites. Several authors have developed experiments and models capable of predicting just such machinability. One of the main parameters often used to characterize the quality of machined surfaces is the cutting force during machining. Several scientific articles based on the trimming of carbon fibre/epoxy laminates have investigated cutting forces and the resulting quality of the machined surfaces [1, 2, 3]. As a result, the cutting tool geometry, as well as the machining parameters utilized, e.g., feed rate and cutting speed, for a given composite material are among the parameters that will directly influence the cutting force magnitude and the part quality. The study by Wang went further by showing the correlation between cutting forces and roughness after trimming [4]. This correlation highlights the interest of predicting cutting forces during machining as they affect the final surface quality.

As a general rule, models developed based on experimental data analysis give better estimations of expected cutting forces than those established analytically or numerically. For example, Rusinek used machining experiences based on unidirectional carbon fibre laminates to develop a mathematical model that can predict cutting forces [5]. His model produced interesting results, with a correlation of around 86% with experimental data. Bérubé [6] and Zaghbani et al [7] also based their study on experimentations, but considered quasi-isotropic carbon fibre laminates with varying thicknesses. To establish their mathematical models, the authors combined influential parameters, e.g., feed rate, cutting speed and thickness, and developed their models with a correlation of 85 to 90% with experimental data. Most studies (theoretical, experimental or based on numerical simulation) lead to similar conclusions regarding influential parameters. The fibre orientation, the feed rate and the cutting speed seem to influence mostly the cutting forces. However, models do not correlate to the point where cutting forces can be predicted 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 influential parameters that are yet to be fully developed in the literature.

The pressure applied during the curing of composite materials greatly affects the quality of finished parts. For example, it is well known that a low pressure leads to high void content. Olivier studied the influence of pressure during curing on the composite void content [8]. His experiment, based on a study of carbon fibre laminates (0°/90°), allowed him to establish a relationship between pressure in the autoclave and void content (Fig. 1.). He observed an exponential decrease in void content with increasing pressure. Later, Ling
repeated the experiment on another kind of carbon fibre/epoxy laminate ([0°/90°]₃s), using a more accurate vacuum hardware detection system [9]. He refined the model developed by Olivier and confirmed the existence of an exponential relationship between pressure and void content. The mechanical properties of the composite are obviously affected by the void content. For instance, Ghiorse highlighted the relationship between void content and Interlaminar Shear Strength (ILSS) for carbon fibre/epoxy laminates [10]. Then, several authors [8, 11, 12] confirmed Ghiorse’s conclusions and refined the experimental results (especially for low values of void content) by using a non-destructive measurement system such as ultrasound. Finally, Bhatnagar showed the influence of the mechanical properties of the material on cutting forces [13]. In his experimental study based on the trimming of carbon fibre/epoxy laminate, he linked the ILSS to cutting forces. These three findings are interesting because they seem to link the pressure applied during the curing of a laminate and the machining cutting forces. To try to improve the prediction of cutting forces, this research aims to experimentally analyse the combined effect of cutting parameters (feed rate and cutting speed) and vacuum pressure during the curing of carbon fibre laminates on composite machinability, which is expressed in terms of cutting forces (Fig. 2.).

2 Methodology

This study is exclusively based on the analysis of experimental data. Carbon fibre/epoxy laminates were first manufactured using various curing pressures. The plates were then machined using various cutting parameters (feed rate and cutting speed), and a Pareto ANOVA analysis was conducted in order to investigate the potential links between curing pressure and the composite machinability.

2.1 Manufacturing

Laminates were made using 12 unidirectional carbon fibre plies and epoxy with lay-up [90°/-45°/45°/0°/45°/-45°]. The carbon fibre was impregnated with the epoxy resin using the wet lay-up process and cured at a temperature of 22°C for 8 hours (Fig. 3.). Three 240 mm x 406 mm plates were produced (Fig. 4.). The vacuum pressure (P_vac) used during curing was 0.39, 0.11 and 0.7 bar for plates 1, 2 and 3, respectively. A one-week post-cure at a temperature of 22°C and pressure of 1 bar was then performed. To prepare the test coupons, each of the three composite plates was cut into two 102 mm x 406 mm plates, using a circular diamond saw. During manufacturing, several assumptions were made: the temperature was constant and equal to 22°C ± 1°C and uncertainty of measurement on vacuum pressure was estimated at ± 0.014 bars.
2.2 Trimming

The composite plates were trimmed at three cutting speeds (N) and four feed rates (f) (Table 1), for a total of 12 machining conditions. Three repetitions were performed for each machining condition in order to reduce measurement errors and dispersion effects. Thus, 36 specimens were cut off for each pressure, for a total of 108 specimens (Fig. 4.).

Table 1. Trimming parameters

<table>
<thead>
<tr>
<th>Cutting speed (rpm)</th>
<th>Feed rate (mm/rev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6683</td>
<td>0.2032</td>
</tr>
<tr>
<td>13366</td>
<td>0.254</td>
</tr>
<tr>
<td>21720</td>
<td>0.400</td>
</tr>
<tr>
<td></td>
<td>0.508</td>
</tr>
</tbody>
</table>

The choice of cutting tool and machining parameters was made in keeping with the conclusions of Bérubé [6]: the cutting tool was a two-flute polycrystalline diamond (PCD) (Fig. 5.). All tests were performed with up-milling and dry conditions. Every trimming test was conducted in the same environment (Fig. 5.), with a CNC (Computer Numerical Control) machine tool, the three-axis Huron K2X10. To characterize the machinability, cutting force components were measured for the 108 specimens in each direction (X, Y, and Z) with a three-axis Kistler 9255 type dynamometer table. The feed direction was along the X-axis. During the trimming tests, the cutting process parameters and cutting materials were the same for every specimen and tool wear effects on cutting forces were neglected. This last assumption was justified by the short length of cut during this experiment as well as the observations/results found with this particular tool in a previous study [6]. Uncertainties during cutting tests are specified in Table 2.
Table 2. Trimming precisions

<table>
<thead>
<tr>
<th>CNC machine tool</th>
<th>Uncertainty of Measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>f</td>
<td>± 0.0001 mm/tr</td>
</tr>
<tr>
<td>Vc, N</td>
<td>± 0.001 m/s; ± 1 rpm</td>
</tr>
<tr>
<td>X-axis</td>
<td>± 2.6%</td>
</tr>
<tr>
<td>Y-axis</td>
<td>± 2.95%</td>
</tr>
<tr>
<td>Z-axis</td>
<td>± 2.9%</td>
</tr>
</tbody>
</table>

The length of the specimens was selected based on the linear acceleration distance of the spindle. If the length was not long enough, expected cutting conditions could be effective only on 50% or 30% of the total specimen length. In this study, the dimensions of cut of the specimens was 50 mm x 30 mm, resulting in 95% of the specimens being cut with desired cutting conditions (Fig. 6).

3 Cutting force analysis

To analyse the cutting forces, the following methodology was selected. An average force representing the raw experimental data as accurately as possible was first estimated. Then, the forces were analysed in order to eliminate outlier data. Finally, a multivariable statistical analysis was carried out.

3.1 Analysis of experimental data

Experimental data was analysed with Matlab, using the following methodology (Fig. 7.):
- An initial force corresponding to the first recorded value was defined (F_{X0}, F_{Y0}, F_{Z0})
- Another force defined the beginning of cutting (F_{Xi}, F_{Yi}, F_{Zi}) calculated from initial forces
- The beginning of computation started after 10 tool rotations (margin of safety)
- Computation lasted for 20 tool rotations and consisted in averaging the absolute value of recorded forces.

3.2 Data selection

In a second step, outlier data was eliminated. For this, the “time” plot (order in which the measurements appear, Fig. 8.) and box-and-Whisker plot (Fig. 9.) were used. The two figures show the date before and after elimination of outlier data.

It can be seen that “time” plots also show whether tool wear has a significant effect on the cutting forces, in which case, the latter would increase regularly.
3.3 Results

After outlier data were eliminated, a Pareto ANOVA analysis was conducted to determine a simple model based on our three input parameters:

- f (mm/rev): feed rate
- N (rpm): cutting speed
- \(P_{\text{vac}}\) (bar): vacuum pressure during curing

This analysis included 1\(^{st}\) and 2\(^{nd}\) degree inputs; for example, \(f^2\) or \(f\times N\) was considered. It should be noted that only 2\(^{nd}\) degree input which have a physical meaning is considered; for example \(P_{\text{vac}}\times N\) is not included, but \(f\times N\), which represents the linear spindle speed, is included.

Figure 10 shows the Pareto chart. This chart ranks factors which influence the output \((F_X)\) significantly in ascending order. In the Pareto charts subsequently presented, input parameters which do not have a significant effect (are below the limit of influence) or which do not have a physical meaning are not presented. Figure 11 shows the effect of each factor on the force component in the feed direction, \(F_X\). For instance, the feed rate and \(F_X\) seem to be linked by a linear relationship. The following is the architecture of the mechanical model:

\[
F_X = f(f, N, N^2, f \times N, P_{\text{vac}}, P_{\text{vac}}^2) \quad (1)
\]

Table 3 shows the correlation between the experimental data recorded and the mathematical model which gives the best results after ANOVA analysis (equation 2). \(R^2\) characterizes the correlation as it is the parameter used by ANOVA analysis to search and optimize the proposed model. The Durbin-Watson test gives an estimation of the residual autocorrelation. This indication shows whether another parameter not taken into account influences the cutting forces.
\[ F_X = 41.310 - 145.499 P_{vac} + 146.56. f \\
- 0.0069881 . N - 109.07 . P_{vac}^2 \\
+ 0.0049484 . f . N \\
+ 2.5910 . 10^{-7} . N^2 \]  
(2)

Table 3. ANOVA reports \( F_X \)

<table>
<thead>
<tr>
<th>Characteristic quantities</th>
<th>Proposed model for ( F_X )</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R^2 )</td>
<td>81.3%</td>
<td>95% - 100%</td>
</tr>
<tr>
<td>Durbin-Watson test</td>
<td>1.59</td>
<td>2 ± 0.3</td>
</tr>
</tbody>
</table>

The same approach is used for \( F_Y \) and \( F_Z \), and the results are shown in Figure 12, 13, 14 and 15 and Tables 4 and 5.

Proposed model:
\[ F_Y = f(f, N, f^2, P_{vac}^2) \]  
(3)

An analysis of \( F_Y \) gives the best results. Values of characteristic quantities are close enough to allow this model to be used to predict \( F_Y \). It is interesting to note that the vacuum pressure during curing does not influence the axial component of the cutting force \( F_Z \), as opposed to the feed \( X \) and normal \( Y \) components. This may be explained by the low magnitude and variability of the axial force due to the null helix angle value of the cutting tool.

Proposed model:
\[ F_Z = 58.136 - 36.905 . f - 0.0079195 . N \\
+ 0.0048375 . f . N + 3.4231 . 10^{-7} . N^2 \]  
(6)

Table 4. ANOVA reports \( F_Y \)

<table>
<thead>
<tr>
<th>Characteristic quantities</th>
<th>Proposed model for ( F_Y )</th>
<th>Target values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R^2 )</td>
<td>94.3%</td>
<td>95% - 100%</td>
</tr>
<tr>
<td>Durbin-Watson test</td>
<td>1.98</td>
<td>2 ± 0.3</td>
</tr>
</tbody>
</table>

An analysis of \( F_Y \) gives the best results. Values of characteristic quantities are close enough to allow this model to be used to predict \( F_Y \). It is interesting to note that the vacuum pressure during curing does not influence the axial component of the cutting force \( F_Z \), as opposed to the feed \( X \) and normal \( Y \) components. This may be explained by the low magnitude and variability of the axial force due to the null helix angle value of the cutting tool.

To describe the effect of the curing pressure more precisely, several Pareto ANOVA analyses were conducted where the \( P_{vac} \) parameter was replaced.
with a function of \( P_{\text{vac}} \) (e.g., \( P_{\text{vac}}^2 \), \( \ln(P_{\text{vac}}) \), etc.). The results obtained are similar to those given by the first analysis, and as a result, it is therefore not possible to identify a better model.

### 3.4 Comparisons

Table 6 highlights the influence of the manufacturing parameter \( P_{\text{vac}} \) based on two analyses: the first takes into account the curing pressure \( P_{\text{vac}} \) and the second reproduces the setup used by S. Bérubé [6], in which \( P_{\text{vac}} \) is not taken into account. Thus, the three previous ANOVA analyses (\( F_X \), \( F_Y \), \( F_Z \)), which consider vacuum pressure \( P_{\text{vac}} \) as an input, are compared to three new ANOVA analyses (\( F'_X \), \( F'_Y \), \( F'_Z \)), which only consider cutting parameters (feed rate and cutting speed) without vacuum pressure.

#### Table 6: Influence of \( P_{\text{vac}} \) on model correlation

<table>
<thead>
<tr>
<th>Correlation: R²</th>
<th>Influential parameters</th>
<th>With ( P_{\text{vac}} )</th>
<th>Without ( P_{\text{vac}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_X )</td>
<td>( f, N, N^2, f.N, P_{\text{vac}}, P_{\text{vac}}^2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_Y )</td>
<td>( f, N, P^2, P_{\text{vac}}^2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_Z )</td>
<td>( f, N, N^2, f.N )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F'_X )</td>
<td>( f, N, N^2, f.N )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F'_Y )</td>
<td>( f, N, P^2 )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F'_Z )</td>
<td>( f, N, N^2, f.N )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The new input (vacuum pressure) improves the correlation by about 3%. This improvement may seem negligible, but at this high level of correlation (80 to 90%), even a slight improvement can be considered important as it draws the three models closer to simple and sustainable predictive mathematical models.

### 4. Conclusions

This study confirms the conclusions of several authors on the correlation between cutting forces and cutting parameters (cutting speed and feed rate) [5, 6, 7]. This correlation is the basis of predictive models for each cutting component. Influential parameters are found to be the:

- Feed rate: \( f \)
- Cutting speed: \( N \) and \( N^2 \) (with constant tool diameter during the study)
- Linear spindle speed: \( f*N \)

The new conclusion which is highlighted in this study is the correlation between cutting forces (\( F_X \) and \( F_Y \)) and curing pressure. It is shown that considering the pressure applied during curing can improve mathematical models, allowing a sustainable and predictive machinability model to be approached. Such a model predicting the cutting forces during machining provides significant advantages for manufacturers, including the prediction of tool wear and surface finish. To improve understanding of the effect of the curing pressure on composite machinability, experiments should be carried out on more levels of pressure on real aerospace grade materials, which will be covered in future work.

### 5. Future work

Future work will focus on the improvement of manufacturing methods:

- Better precision of vacuum pressure;
- Pre-impregnated composite fibres will be used;
- More levels of pressure will be considered in the design of experiments.

In addition, to bring the study closer to an industrial context, it would be interesting to change the manufacturing protocol for the composite plates processing. For instance, the use of an autoclave is recommended.

### References

