Investigation of CFRP machining with diamond abrasive cutters, Journal of Composite and Advanced Materials

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ABSTRACT. *Diamond abrasive cutters are more and more used for industrial applications of CFRP laminate machining, due to their resistance to abrasion and low cost. The objective of the approach is to improve productivity during trimming operations, by choosing adapted tools and cutting parameters. The objective of this article is to determine to what extent feedrate and spindle speed can be increased. To do so, specific cutting energy (Esp) and cutting forces are studied. Designs of Experiments and ANOVA are performed in order to analyze the influence of tool (grit size, level of nickel and diameter) and process (feed per revolution and cutting speed) parameters. It shows that high cutting speed is favourable to the cut due to thermal effects. Conversely, the study of specific cutting energy reveals that the feed increase is limited by diamond grit size and level of nickel due to the saturation of the tool intergrit space.*

RESUME. *Les fraises à concrétions diamantées sont de plus en plus utilisées industriellement pour le détourage de composites, CFRP laminés notamment, en raison de leur résistance à l'abrasion et de leur faible coût. L'objectif des travaux est d'améliorer la productivité en optimisant le choix des paramètres opératoires. Il s'agira donc déterminer dans quelle mesure l'avance et la vitesse de rotation de la broche peuvent être accrues. Pour cela, l'énergie spécifique de coupe (Esp) et les efforts de coupe sont étudiés. Des plans d'expériences et ANOVA ont été effectués afin d'analyser l'influence des paramètres de l'outil (granulométrie, niveau de sertissage et diamètre) et du procédé (avance et vitesse de coupe). Il est montré que des vitesses de coupe élevées sont favorables à la coupe, grâce aux effets thermiques. Par contre, l'étude de l'énergie spécifique de coupe a révélé que l'avance est limitée par la granulométrie et le niveau de sertissage, à cause d'une saturation du volume libre inter-granulaire de l'outil.*

KEYWORDS: Machining, diamond abrasive cutter, CFRP, laminate, trimming, force.

MOTS CLES: Usinage, fraise à concrétion diamantée, CFRP, laminé, détourage, effort.

Extended abstract:

☛ Diamond abrasive cutters are more and more used for industrial applications of CFRP laminate machining, due to their resistance to abrasion and low cost. The objective of the approach is to improve productivity during trimming operations, by choosing adapted tools and cutting parameters. The objective of this article is to determine to what extent feedrate and spindle speed can be increased. To do so, specific cutting energy and cutting forces are studied. Design of Experiments and ANOVA are performed in order to analyze the influence of tool (grit size, level of nickel and diameter) and process (feed per revolution and cutting speed) parameters.

It shows that high cutting speed is favourable to the cut due to thermal effects. Indeed, complementary measures with thermal camera have revealed an increase of cutting temperature with spindle speed. Besides, Kinemat test have shown that the mechanical properties of carbon-epoxy laminate decrease with temperature. They drop after the glass transition temperature, but it is not reached during the cut at high spindle speed. Thus, the maximum spindle speed should be used.

The study of specific cutting energy has revealed that the increase of feed is limited by a saturation of the tool intergrit space with CFRP chips. In order to avoid the phenomenon, feed values should be lower than a given threshold. It limits productivity. The threshold is higher with larger diamond grit size and lower level of nickel.

It was also found that, under identical feed and cutting speed, the influence of tool diameter on specific cutting energy and force is negligible. In order to analyse it, tools were scanned, the tool numerical model rebuilt and the process simulated. It revealed that, in spite of the random grit distribution around the tool, the average chip thickness removed by grits on a given level of the tool is similar whatever the diameter, which is not intuitive. It explains why specific cutting energy and force are not affected by tool diameter. Besides, the same analysis explains why the influence of grit size on specific cutting energy and force is negligible, which is not intuitive too.

1. Introduction

Manufacturing processes of composite materials leads to finishing operations, like drilling and trimming, so as to eliminate excess of material from polymerized parts. It is necessary in order to achieve dimensional tolerances and surface quality requirements. However, the machining of composite laminates is difficult because of their mechanical and thermal properties: heterogeneity, anisotropy and low thermal conductivity (Teti, 2002). Moreover, their high abrasiveness, which is mentioned by (Latha *et al.*, 2009) for drilling and (Furet *et al.*, 2005) for milling, causes excessive tool wear. (Davim *et al.*, 2005) studied the milling of CFRP with carbide tools and obtained good surface roughness. But they have a short tool life, especially in CFRP (Carbon Fibre Reinforced Polymer) due to its abrasiveness (Teti, 2002). During their study on orthogonal cutting, (Wang *et al.*, 1992) proposed PCD (Poly Crystalline Diamond) endmill as an alternative. Higher feedrate can be used and higher product quality is obtained. However, the costs are significant and they are very brittle, as highlighted by (Sheikh-Ahmad, 2009). That is why new tools, such as diamond abrasive cutters and discs, have been specifically developed for CFRP trimming operations. This tool technology, which is constituted of diamond grits, improves tool life and productivity as well as reduces costs. For example, a PCD tool can trim 10 meters of CFRP before being worn, whereas a diamond tool can machine more than 300 meters. Many works have been carried out with metal-bonded diamond tool. However, they mainly concern finishing operations using diamond grinding wheels in metal (Teicher, 2008), metal matrix composite (Anad *et al.*, 2009) or ceramic matrix composite applications (Li *et al.*, 2007) (Tawakoli *et al.*, 2011). There is a lack of research concerning the performance of diamond abrasive cutters during trimming operations. Only (Colligan *et al.*, 1999) performed experiments with similar geometry of diamond abrasive cutters in composite material. They essentially characterized quality of trimmed surfaces, which is correlated to the tool grit size.

The paper presents an investigation of CFRP machining with diamond abrasive cutters. The objective is to determine to what extent feedrate and cutting speed can be increased, in order to optimize productivity. For this reason, specific cutting energy (*Esp*) and cutting forces are analyzed in order to identify possible limiting phenomena. The influence of five parameters is studied: feed per revolution, cutting speed, diamond grit size, level of nickel and tool diameter. Experiments have been performed and analysed by ANOVA. Limiting phenomena are researched and lead to practical recommendations for the optimization of productivity, through the optimal choice of process parameters.

2. Experimental procedure

2.1. *Set-up*

A 9.1 mm thick laminate of T800-M21 (Hexcel) was used to carry out the experiments. The laminate was composed of 35 plies of unidirectional graphite fibre fabric (0.26 mm thick). The matrix was a thermosetting epoxy resin M21. Lay-up sequence was (0/-45/90/90/45/90/90/45/0/-45/90/90/ 90/45/90/-45/90/-45/90)2s.

Trimming tests were carried out on a three-axis Huron KX30 milling machine, equipped with a 28000 RPM - 40 kW Kessler spindle. External and internal water-based coolant was used. The depth of cut corresponded to the part thickness and the width of cut to the tool diameter, as usual in rough trimming. Feedrate direction corresponded to the 0° external ply. Figure 1 presents the experimental set-up.

During cutting tests, the spindle power consumption was measured with a DigitalWay device. The specific cutting energy *Esp* (W/cm3/min) was deduced from the average power values, by dividing by the material removal rate (product of width of cut, depth of cut and feedrate) once the power corresponding to idle rotation subtracted. Note that it is homogenous to a pressure but those are the usual name and unit. Cutting forces were also measured with a Kistler dynamometer table. Contrary to endmills, diamond abrasive cutters lead to constant cutting forces during cuts. So, for each run, average values of feed force *Ff* and normal force *Fn* were evaluated. Then, the cutting forces resultant *F* was obtained and analysed.

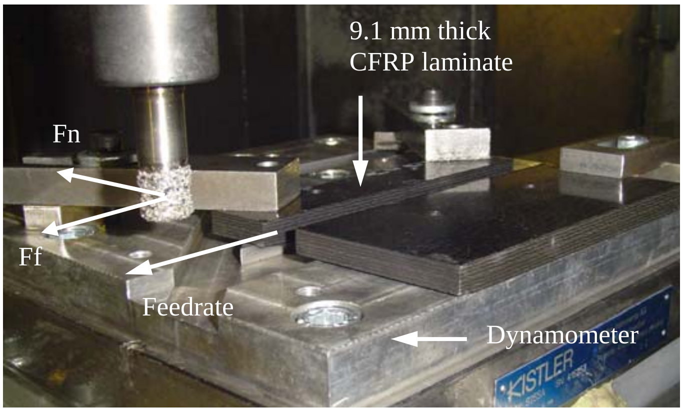

Figure 1. *Experimental set-up.*

2.2. Diamond abrasive cutters

The diamond abrasive cutters used during the experiments were composed of natural diamond grits, fixed with a nickel bond on a cylindrical body by electro deposition. Several parameters characterize the tools. Grit size is the most important one. Different grit sizes *G* are proposed by manufacturers, from very small ones used in grinding applications, to large ones used in the present cutting application. However, limits results from the tool manufacturing process, depending on tool diameter ∅. Indeed, deposing large grits on a small diameter is difficult. Another parameter describing diamond cutter is the level of nickel, noted *Ln*, which is defined as the ratio nickel height to grit size (expressed in %). The larger the level of nickel is, the deeper the grits are in the bond. Table 1 presents the nine tools that were used during the experiments.

N°	Ø (mm)	Grits size (µm)	Level of nickel (%)
1	16	427	50
2	16	602	50
3	16	852	50
4	16	852	50
5	16	1182	50
6	25	852	50
7	12	852	50
8	16	852	50
9	16	852	65

Table 1. *Presentation of the diamond abrasive cutters.*

2.3. *Control factors*

The aim of the study is to determine relevant process parameters for CFRP trimming operations with diamond abrasive cutter. Factors that might limit productivity must be identified. Two categories of parameters were investigated: tool parameters and cutting conditions.

Cutting conditions were studied through the feed per revolution and the cutting speed. Several diamond abrasive cutters were used. Four diamond abrasive grit sizes were studied: 427, 602, 852 and 1182 µm. Tools diameter influence was also considered through three levels: 12, 16 and 25 mm. Moreover, two different levels of nickel were tested: bond matrix covered 50% of the diamond grits, excepted for tool 9 with 65% (Table 1).

An approach with experimental design has been carried out to analyze the influence of tool and process parameters on the cut. Different Designs of Experiments (DoE) were constructed in order to reduce the number of cutting tests. Moreover, technical constrains resulting from the tool manufacturing process and from dangerous sets of cutting conditions were take into account. Consequently, the tests were divided into three designs of experiments that are presented in Table 2. In order to determine the effects and interactions significances of the parameters, analyses of variance (ANOVA) were carried out for the whole DoEs. A 95% confidence level was applied to all dependent variables. ANOVA tables can be found in annex 1 and the results are presented and discussed in the following section.

N° DoE	Symbols	Machining parameters	Units	Level 1	Level 2	Level 3	Level 4
1	f_1	Feed per revolution	mm/rev	0.1	0.23	0.36	0.5
	$ø_1$	Diameter	mm	12	16		
	V_1	Cutting speed	m/min	400	600	800	1000
2	f_2	Feed per revolution	mm/rev	0.03	0.1	0.16	0.23
	G_2	Abrasive grits size	µm	427	602		
	V_2	Cutting speed	m/min	1000	1400		
3	f_3	Feed per revolution	mm/rev	0.1	0.23	0.36	0.5
	G_3	Abrasive grits size	µm	852	1182		
	V_3	Cutting speed	m/min	1000	1400		

Table 2. *Experimental parameters.*

3. Results and discussion

3.1. *Influence of cutting speed*

The effect of cutting speed on specific cutting energy and force is low, as illustrated in Figure 2. The thermal effects in the CFRP laminate can explain the low decrease. Indeed, complementary tests with thermal camera indicated that the local temperature of trimmed surface increases with cutting speed (Figures 3a and 3b). Besides, tests were performed on a Kinemat device in order to observe the mechanical properties evolution during a temperature increase. The torque necessary to impose a given angular deformation on a strip specimen of the CFRP laminate is measured during the temperature increase (blue curve on Figure 3c). It was observed that, before reaching the glass transition temperature (identified at *Tg* = 240°C) where they collapsed, mechanical properties slowly decrease of 15% between 40 and 210°C. Thus, chip removal becomes easier at higher temperature. Therefore, the low decrease of specific cutting energy and forces during trimming (Figure 2) can be explained by the CFRP thermal behaviour. However, during our cutting tests, *Tg* was not reached because no severe decrease of specific cutting energy was observed. Consequently, the material integrity was not affected.

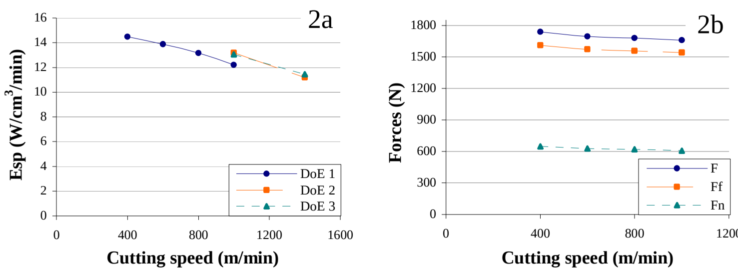

Figure 2. *Effect of cutting speed on specific cutting energy (a) and forces (b).*

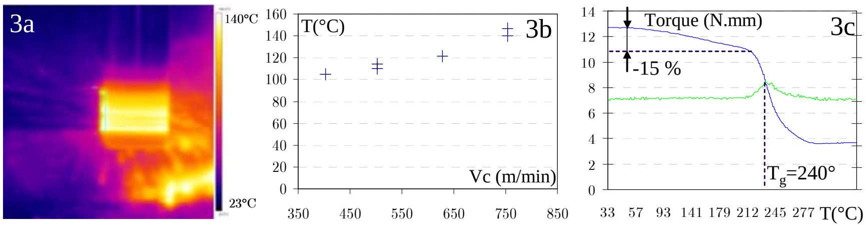

Figure 3. *Measure of cutting temperature (a and b) and identification of mechanical property by Kinemat test (c).*

It can be concluded from the experiments that the highest cutting speed, i.e. maximum spindle speed, is recommended, since it improves productivity.

3.2. *Influence of grit size and feed per revolution*

Firstly, it can be noticed on Figure 4b that the cutting force levels are very close, whatever the tool grit size; when identical feeds are considered. It can be explained by the fact that the chip thickness removed by a given grit is almost the same whatever the grit size. It was proven by tool scanning and process simulation with the real tool geometry, for each tool with a different grit size. Computations are explained in section 3.4.

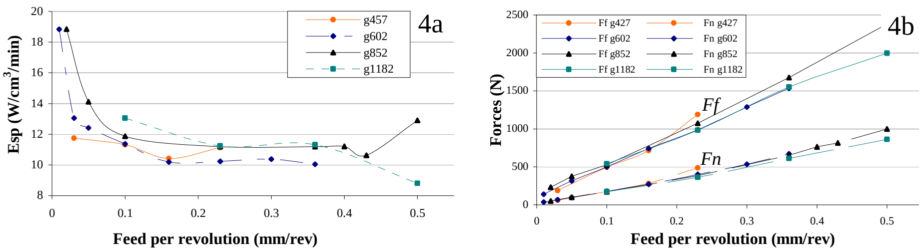

Figure 4. *Influence of feed per revolution and grits size on (a) specific cutting energy and (b) forces.*

Figure 4a presents the evolutions of specific cutting energy in relation to feed and grit size. It can be noticed that three domains appear. Particular phenomena are revealed at low and high feed by the increases of specific cutting energy. They are explained in the following sections. Between them, a central domain leads to adequate cutting conditions for the diamond abrasive cutter. A low decrease can be noticed on this domain that suggests the use of high feeds, while avoiding the high feed phenomenon.

Levels of feed force *Ff* and normal force *Fn* are interesting (Figure 4b). Indeed, during classical metal machining with endmill, *Fn* tends to be higher than *Ff*. On the contrary, during machining using diamond abrasive cutters, normal forces are 40% less than feed force. It is due to higher negative rake angles on grits.

3.2.1. *Cutting phenomenon at low feed*

The presence of a limiting phenomenon at low feed per revolution can be clearly identified in Figure 4a. Indeed, the specific cutting energy significantly increases when feed per revolution is smaller than a given threshold; its value depends on grit size. When grit size is larger, the threshold value is higher. Figure 4a shows that 602 µm and 852 µm grit sizes reached this critical threshold. Lower feed per revolution should have been used to observe a similar phenomenon in the other tools.

When the feedrate is low, the chip thickness is small. Consequently, specific cutting energy that is necessary to remove material rises. (Mondelin *et al.*, 2010) have also noted this phenomenon during scratching tests on the same material, due to higher proportion of friction between the grit cutting face and the workpiece.

3.2.1. *Cutting limit at high feed*

The presence of a second limiting phenomenon can be observed in Figures 4a and 4b concerning 427 µm and 852 µm grit sizes. When feed per revolution reaches a critical threshold, respectively 0.16 mm/rev and 0.36 mm/rev for grit size of 427 µm and 852 µm, specific cutting energy quickly increases. The tools then saturate, depending on their grit size. In the case of the tools with 602 µm and 1182 µm grit sizes, the critical threshold was not reached due to the use of insufficient feeds.

The loading of the diamond abrasive cutter can explain this rise of specific cutting energy. (Ghosh *et al.*, 2008) documented the same phenomenon for metal grinding using wheels. During the machining with diamond abrasive cutters, chips are accumulated in the intergrit space, until the grits exits from material with tool rotation. The chips are composed of small CFRP aggregates. If the feed per revolution is too high, the chips do not have enough space to lodge between grits before being evacuated. The cutting mechanism is deteriorated and specific cutting energy increases along with forces. If the feed per revolution then decreases, the chip flow decreases and can be evacuated normally.

Figure 4a also reveals that the chip removal limit is reached sooner with a small grit size. Indeed, when grit size is smaller, the intergrit space is lower due to higher grit density. Thus, the feed critical threshold is lower for a smaller grit size. To avoid tool saturation, the feed per revolution must be chosen in relation to grit size and especially the intergrit space. Considering our experimental results, the maximum feed per revolution can be set at about 50% to 60% of grit size. So, tool grit size is an important parameter for optimizing productivity.

3.3. *Influence of level of nickel and feed per revolution*

When low feed per revolution is used, specific cutting energy and forces have similar levels, whatever the level of nickel (Figure 5). However, saturation is reached earlier with a higher level of nickel at a high feed, as shown by the deviations of forces and specific energy values at 0.5 mm feed. In fact, when the level of nickel is greater, the intergrit space is smaller. Therefore, a diamond abrasive cutter with a higher level of nickel is saturated before a cutter with a lower level of nickel. Thus, a low level of nickel is recommended in order to improve productivity. Nevertheless, it must be large enough to hold the grits in spite of cutting forces. This requires a compromise between the mechanical strength of the tool and its productivity. The limits concerning the tool manufacturing process must also be taken into account. It results that an average value of 50% is suitable.

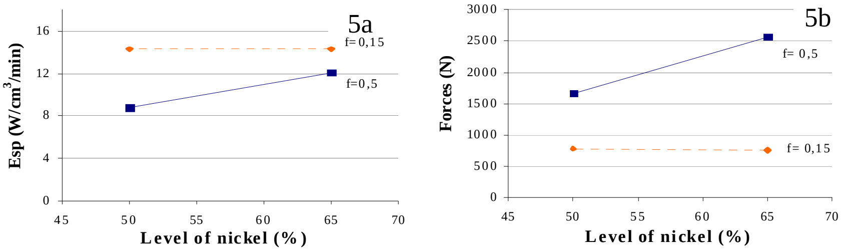

Figure 5. *Influence of level of nickel on (a) specific cutting energy and (b) Forces.*

3.4. *Influence of tool diameter and feed per revolution*

The results presented in Figure 6 should be considered with identical cutting speeds. Indeed, the effect of cutting speed presented in section 3.1 must be removed to avoid misinterpretations. Then, the influence of tool diameter can hence be studied. Low deviations can be observed in Figure 6a. The larger the diameter is, the higher the specific cutting energy is. In Figure 6b, the cutting force levels are very close whatever the tool diameter, under identical feedrate.

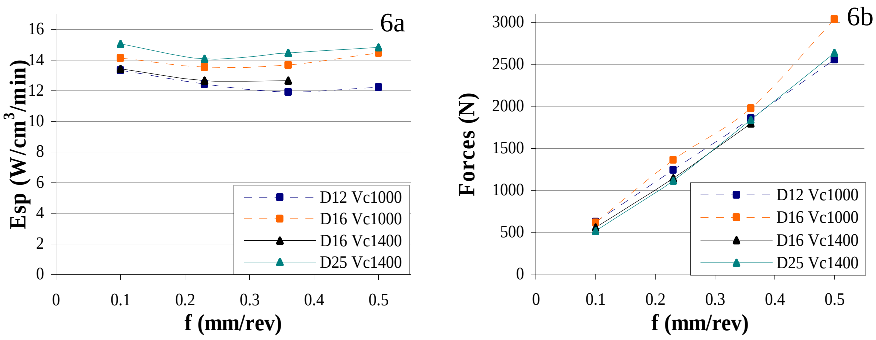

Figure 6. *Influence of tool diameter on (a) specific cutting energy and (b) forces, in relation to feed per revolution and cutting speed.*

It can be explained by the chip thicknesses removed by grits. In order to discuss this hypothesis, a specific device has been developed for tool scanning. It leads to the real tool geometry (Figure 7a). Then, the tool is discretized into horizontal slices and the cutting process is simulated in relation to the feed per revolution. Grits that participate to the cut are identified and their associated chip thickness *hc* is evaluated (Figure 7b). In this way, the mean chip thickness can be calculated. Figure 7c presents the results for different tool diameters. Counterintuitively, it shows that the mean chip thickness varies few in relation to tool diameters. Consequently, it explains why specific cutting energy and cutting force values are similar.

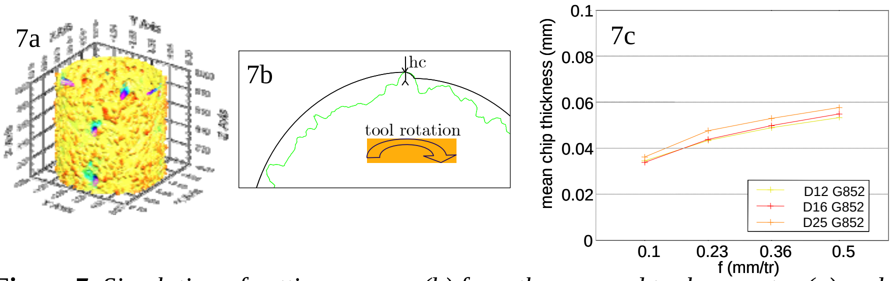

Figure 7. *Simulation of cutting process (b) from the scanned tool geometry (a) and analysis of the mean chip thickness in relation to feedrate and tool diameter (c).*

Finally, it results from the low effect of tool diameter that small diameters are recommended in order to reduce width of cut and spindle power. Limits exist due the tool strength and to the tool manufacturing process. Indeed, it is difficult to set large grits on a small diameter. Thus, there is a minimum tool diameter on which a given grit size can be fixed correctly.

4. Conclusion

The paper investigates the CFRP machining with diamond abrasive cutters. The aim is to maximize productivity, through the increase of feedrate and cutting speed.

The effects and interactions of tool grit size, level of nickel, tool diameter, feed per revolution and cutting speed were studied by analysing the cutting forces and the specific cutting energy (issued from spindle power).

Limiting cutting phenomena were revealed, at low and high feeds. The latter is of major interest. Saturation of the diamond abrasive cutter occurs when too high feedrate is used, beyond a given threshold. An aggregate of CFRP chips saturates the tool intergrit space. This threshold is a limit to productivity. The use of large grit size and low level of nickel increases the value of the threshold. Indeed, intergrit space is more important and tool saturation occurs at higher feedrate.

Besides, it was found that tool diameter and cutting speed have low effects on cutting force and specific energy. Thus, small diameter should be favoured and the highest cutting speed is recommended. The latter improves the cut due to thermal effects; but the material integrity is respected, since the glass transition temperature *Tg* is not reached during the cut.

Acknowledgments

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Annex A:

a - DoE1						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_1	13.22	3	4.41	26.95	4.07	Y
$ø_1$	10.45	1	10.45	63.89	5.32	Y
V_1	25.60	3	8.53	52.17	4.07	Y
f_1 / $ø_1$	4.87	3	1.62	9.92	4.07	Y
f_1 / V_1	4.01	9	0.45	2.72	3.39	N
$ø_1$ / V_1	0.52	3	0.17	1.06	4.07	N
Error	1.47	9	0.164			
Total	60.14	31				
b - DoE2						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_2	13.11	3	4.37	158.58	9.28	Y
G_2	0.07	1	0.07	2.634	10.13	N
V_2	15.82	1	15.82	574.07	10.13	Y
f_2 / G_2	3.43	3	1.14	41.54	9.28	Y
f_2 / V_2	0.21	3	0.07	2.566	9.28	N
G_2 / V_2	0.03	1	0.028	0.97	10.13	N
Error	0.083	3	0.028			
Total	32.77	15				
c - DoE3						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_3	9.51	3	3.17	9.80	9.28	Y
G_3	0.30	1	0.30	0.93	10.13	N
V_3	10.39	1	10.39	32.13	10.13	Y
f_3 / G_3	9.60	3	3.20	9.89	9.28	Y
f_3 / V_3	0.45	3	0.15	0.47	9.28	N
G_3 / V_3	0.69	1	0.69	2.12	10.13	N
Error	0.97	3	0.32			
Total	31.91	15				

Table A.1. *ANOVA table for Esp (a) DoE1, (b) DoE2, (c) DoE3.*

a - DoE1						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_1	20823276	3	6941092	7064,44	3,86	Y
$ø_1$	387250	1	387250	394,13	5,12	Y
V_1	26440	3	8813	8,97	3,86	Y
f_1 / $ø_1$	376583	3	125528	127,76	3,86	Y
f_1 / V_1	11238	9	1249	1,27	3,18	N
$ø_1$ / V_1	6355	3	2118	2,16	3,86	N
Error	8843	9	983			
Total	21639985	31				

b - DoE2						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_2	2317371	3	772457	918,02	9,28	Y
G_2	23402	1	23402	27,81	10,13	Y
V_2	614	1	614	0,73	10,13	N
f_2 / G_2	26070	3	8690	10,33	9,28	Y
f_2 / V_2	957	3	319	0,38	9,28	N
G_2 / V_2	59	1	59	0,07	10,13	N
Error	2524	3	841			
Total	2370998	15				

c - DoE3						
Factor	SS	DoF	V	Fratio	Ffisher	Signif
f_3	6978414	3	2326138	874,19	9,28	Y
G_3	125047	1	125047	46,99	10,13	Y
V_3	3678	1	3678	1,38	10,13	N
f_3 / G_3	155116	3	51705	19,43	9,28	Y
f_3 / V_3	8755	3	2918	1,10	9,28	N
G_3 / V_3	1961	1	1961	0,74	10,13	N
Error	7983	3	2661			
Total	7280955	15				

Table A.2. *ANOVA table for F (a) DoE1, (b) DoE2, (c) DoE3.*