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STATISTICAL COMPARISON OF TAGUCHI METHOD AND FULL FACTORIAL ON THE QUALITY OF DRILLING ON FRP COMPOSITE
27th COBEM

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Abstract. Fiber-reinforced composite materials have gained immense popularity in various industries as a viable alternative to metallic materials due to their exceptional mechanical and physical properties. These materials offer a high strength-to-weight ratio, superior fracture resistance, and excellent chemical stability, making them highly desirable for applications that demand lightweight and durable materials. Among these composite materials, the FRP (Fiber reinforced plastic) has been used in large-scale in many industries and the necessity to machine them is a big concern due to the possibility of damaging the material and decrease its strength. Since these problems can render a part useless the normal approach is to test the products, but this attitude can generate a large financial cost and consume a lot of time because of that some statistical methods can be used to make this process more efficient. This research aims to verify the accuracy of the Taguchi method for experiment design, when compared to a full factorial analysis. The goal is to apply both methods to verify and optimize machining parameters based on their influences on the quality of holes; this quality is measure using both qualitative and quantitative factors, by the Davim delamination factor. The delamination is analyzed in the entry and exit of holes resulting from the drilling process in fiber-reinforced plastic, in an industrial setup. To carry this analysis a data set on the drilling of FRP previously done by the full factorial method was used as a base, the statistical method applied received a limited subset of the complete factorial analysis, and the results were compared. The full factorial set comprise of five types of drill bits (118°, 130°, 135°, 140° and E-90°) three feed rates (0,08mm/s ;0,10mm/s ;0,30mm/s) and three cutting speeds (10m/min, 28m/min 57m/min) in two materials ([0°,90°];[-45°,45°]). Both the entry and the exit of the hole were analyzed and a scored based on the eccentricity and delamination area and by sing Davim method a value was attributed to is quality. The full factorial analysis comprises of 45 tests for every material side and by using a L9 adapted orthogonal array a reduction of 5 times was achieved in the necessary performed experiments, witch reduced from 45 to only 9. For both methods 2 statistical analysis were performed the mean value analysis and the ANOVA. The results obtained by the Taguchi method were mixed, it correctly predicted all the mean values of cutting speed, feed rates and 3 out of the 5 drill bits (118°, 140° and E-90°), but failed to predict the correct values for 130° and 135°. Furthermore, in the ANOVA analysis Taguchi descanted cutting speed as a significant factor in the entry of both sheets. In conclusion, for the entries and the adapted setup the Taguchi method was not a valid method for the scientific studies but however it shown great potential in industrial setups were speed and cost is the upmost priority. The information obtained in this research intends to expand information and knowledge on this subject.
Keywords: Drilling, Taguchi´s method, Composite Materials, Statistical Analysis

1. INTRODUCTION

Dr. Genichi Taguchi to AT&T Bell Laboratories first introduced the Taguchi method in 1980. Nowadays Taguchi method is commonly used continuously to improve the quality of the product in place of statistical process control (SPC), the Deming approach, and the Japanese concept of total quality control. SINGH, (2019)

Fiber-reinforced polymer (FRP) composites are composed mostly of a tough matrix material reinforced by high-strength filaments and non-reinforcing fibers. The appropriate combination of these materials results in well-designable and superior mechanical properties. These composites usually have high specific tensile strength and high elasticity modulus, good geometrical stability, as well as electrochemical and corrosion resistance. And can be used in a variety of sectors like civil construction, sports and domestic. Because of that typical materials are replaced by FRPs particularly Carbon Fiber Reinforced Polymer (CFRP) sort during a range of economic, domestic, and engineering applications. Shunmugesh, et al. (2017). Hegde, et al. (2019). Poór, et al. (2021).

Even though CFRP parts are often manufactured to ready-shape, machining operations (e.g. drilling, edge or pocket milling) are often unavoidable to meet dimensional and functional requirements. Selective material removal known as machining is one of the most popular manufacturing processes. And hole drilling and edge trimming are the most demanded machining operations, because of that is of upmost importance study the effects of drilling in CFRP materials. Kechagias, et al (2021). Geier, et al. (2019). Geier, et al. (2021).

2. MATERIALS, METHODS AND EQUIPMENTS

For carrying out drilling tests on composite materials in order to minimize the damage around the holes, it is necessary to control and correlate the greatest number of process variables. In this chapter, all stages of this research are detailed, such as choice of specimen material, sample-manufacturing process, drilling processes, choice of cutting parameters, types of drills, equipment used, acquisition from the images of the holes, the methodology used to calculate the factor of delamination.

Due to the wide range of glass fiber fabrics available, the materials chosen are the ones with most use cases among medium-sized boat manufacturers. These fiberglass fabrics can be combined into different weights and fiber types. For the fabrication of the specimens were used three different types of fabric

Discontinuous and disoriented fabric: The commercial name for this product is "blanket". The blanket has short, randomly ordered strands of fiber held together by a bonding material that dissolves when it exposed to the resin. This blanket has a weight of 450g/m². This material name in this study is "blanket 450".

Continuous and oriented fabric [-45°/45°]: This material is made up of two continuous and crossed fabrics, each of which weighs 228 g/m², and are oriented to each other at 45° and -45°. In addition, they are united with a 275g/m² blanket through sewing, thus totaling a material with 731g/m², which in this research will be called as it is commercially known "fabric 1308."

Continuous and oriented [0°/90°] fabric: This fabric is formed by two continuous and crossed fabrics, one fabric is oriented at 0° and the other at 90°, each weighing 300g/m². In addition, they are united with a 275g/m² blanket through sewing, thus totaling a material with 875g/m² that will also be called by its commercial name, that is, "fabric 1808".
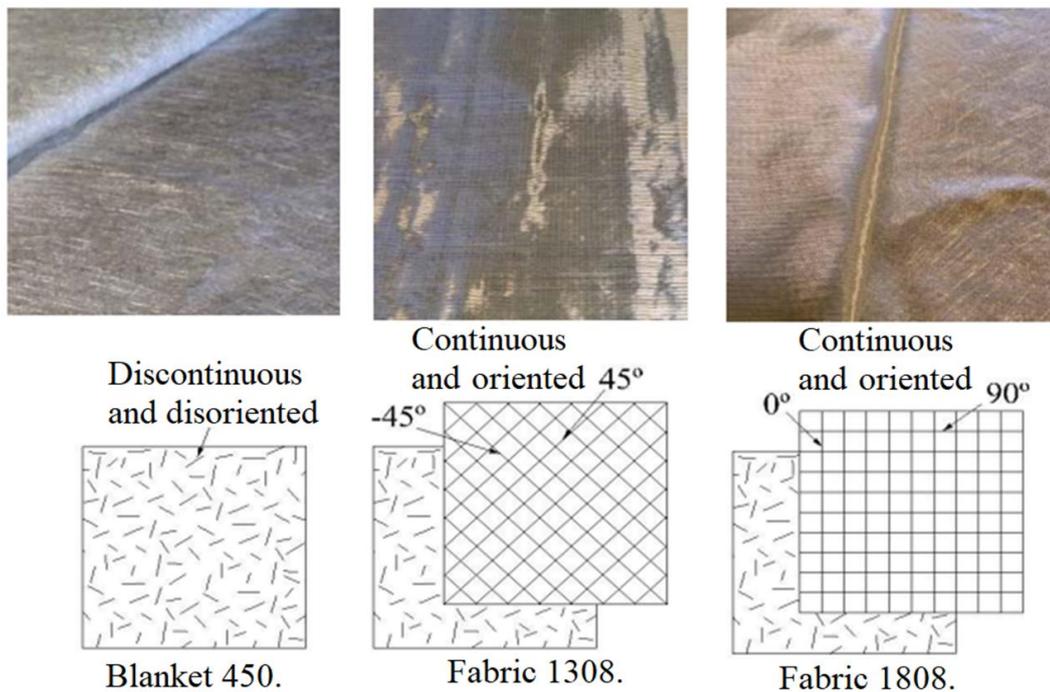

Figure 1. Schematic diagram of the control strategy. Adaptation of Acacio (2015)

Two planes of lamination were developed for the samples: Option A which consisted of 3 layers of Blanket 450 and 3 layers of fabric 1808 for 6 layers in total and option B which consisted of 3 layers of Blanket 450 and 4 layers of fabric 1808 7 layers in total. Each lamination plane has different numbers of layers and types of fabrics, thus obtaining two types of specimens, with different mechanical properties, due to weights and orientations of the fibers.

2.1   Sample dimentions

The specimen's dimensions are determined so that 80 holes could be drilled, divided into two groups of 40 holes each. Considering that the spacing between the centers of each hole would be 20mm, plus the diameter of the drill added to the spaces needed to fix the specimens, it was determined that each one of them should form square plates with dimensions of approximately 230mm, as is depicted in Figure 2.
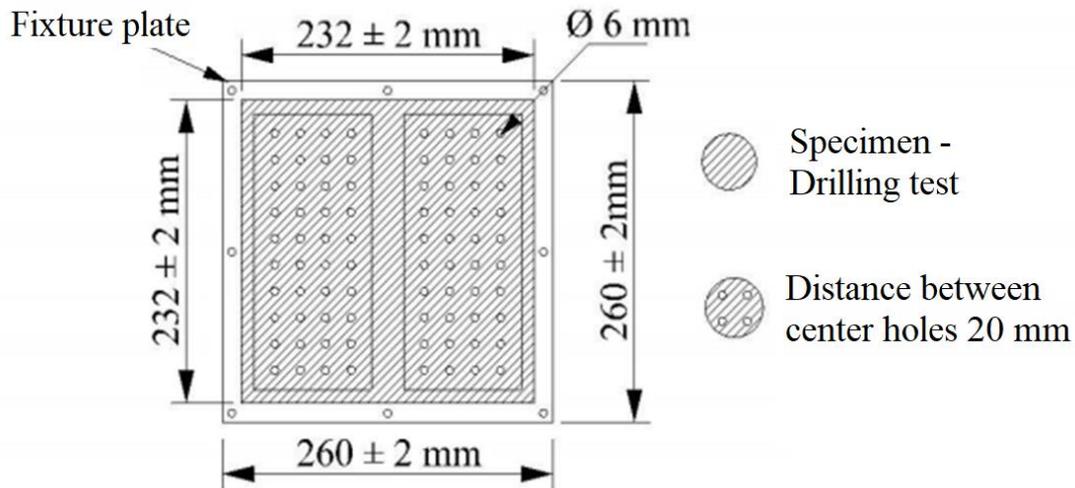

Figure 2. Dimensions of the specimen. Adaptation of Acacio (2015)

The lamination process was manual. As it was intended to test two different lamination planes, it was necessary to use two glass plates (molds) at the same time, to maintain the same temperature and humidity conditions for both tests, for the specimens. These molds were placed on level tables to ensure a surface finish without warping. The glasses received a waterproofing treatment where 8 coats of wax were applied to ensure that the laminated material did not adhere to the molds. With all the materials already cut, the impregnation of the glass fibers with resin on the mold began. The fiber layers were stacked and impregnated one by one, as can be seen in Figure 3.

Figure 3. Lamination Process. Adaptation of Acacio (2015)

The specimens remained on the molds for a period of approximately 72 hours at room temperature before being demolded and machined to sizes and quantities desired, as shown in Figure 2. The drilling tests were carried out in a machining center installed in the Machining and Numerical Control Laboratory (USICON) of the Mechanical Engineering Department of the Federal University of Santa Catarina, manufactured by the company CHARLES model MVC 955 equipped with a SIEMMES 840Di numerical control.

The drilling tests were carried out without cooling and lubrication. Due to the type of chips generated by drilling in dry composite materials, which are usually a powder, it was necessary to use a vacuum cleaner to help remove the chips and prevent them from spreading in the machine tool, as shown in Figure 4.
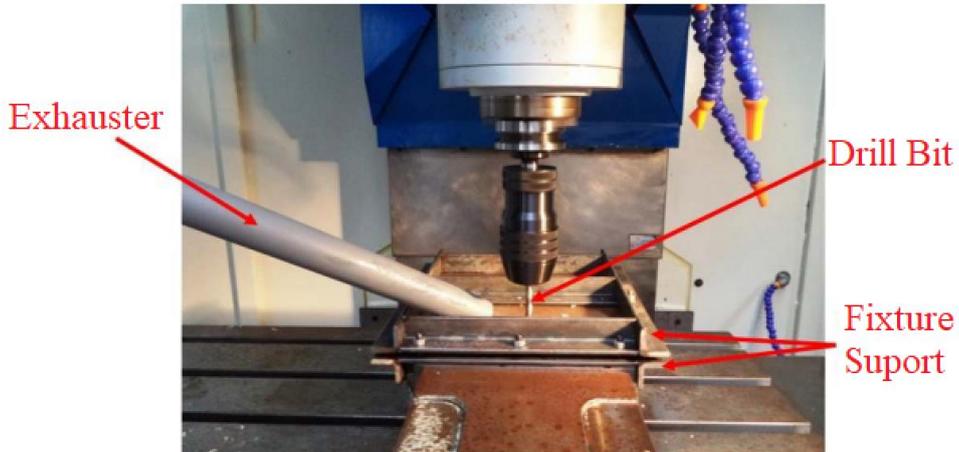

Figure 4. Machine Setup. Adaptation of Acacio (2015)

The drill bits used in the experiments are shown in the Figure 5 below, except for the E-90 drill bit, none of them are manufactured with composite cutting as the primary focus of work. To maintain a sharp and new edge on the drill bits tested after each 40 holes cut the drill bits were replaced with a brand new.
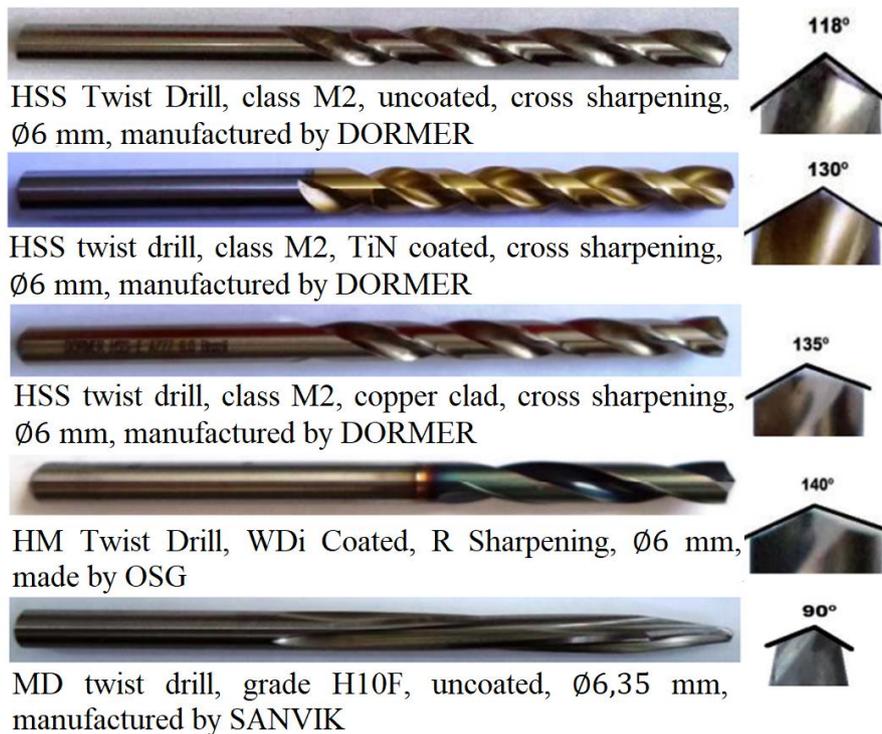
Figure 5. Drill bits used. Author (2023)

In order to define which parameters to use small drilling tests were carried out extrapolating the maximum and minimum values. The experiments variables are shown in the table 1 below.

Table 1. Experiment Variables. Author (2023)

Drill bits	118°	130°	135°	140°	E-90°
f (mm)	0,08	0,15	0,30		
v_c (m/min)	10	28	57		
Sample	[0°/90°]	[-45°/45°]			

The holes were scanned using a stereoscopic microscope OPTON, model TNE – 02B, with a magnification of 7x to 30x, which provided images like the one in Figure 6. After scanning all the holes, public domain software from the National Institute of Health of the United States called ImageJ (ImageJ, 2014) was used to treat the images with tone, contrast and brightness adjustment, in addition to the use of a binary filter to better determine the damaged area, as shown in Fig. 16B.
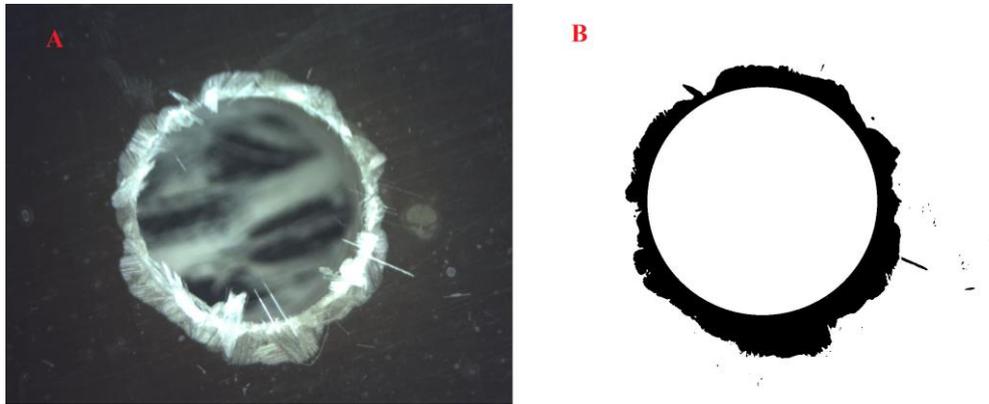
Figure 6. A Stereoscopic microscope picture B Binary filter applied to stereoscopic microscope picture. Author (2023)

With the objective of comparison and better representation of the damage of the holes, four methods of calculating the delamination factor were applied. To quantify the damage of the holes in this study, the adjusted delamination factor (Fda) method proposed by DAVIM et al. (2007), as used by Xu, et al. (2023). Expressed by Eq. (1), Eq. (2), Eq. (3) and Eq. (4)

$$F_d = \frac{D_{max}}{D_0}, \tag{1}$$

$$F_{da} = F_d + \frac{A_d}{(A_{max} - A_0)}\left(F_d{}^2 - F_d\right), \tag{2}$$

$$A_{max} = \pi \frac{D_{max}{}^2}{4}, \tag{3}$$

$$A_0 = \pi \frac{D_0{}^2}{4}, \tag{4}$$

Figure 7. Davim variables. Acacio (2015)
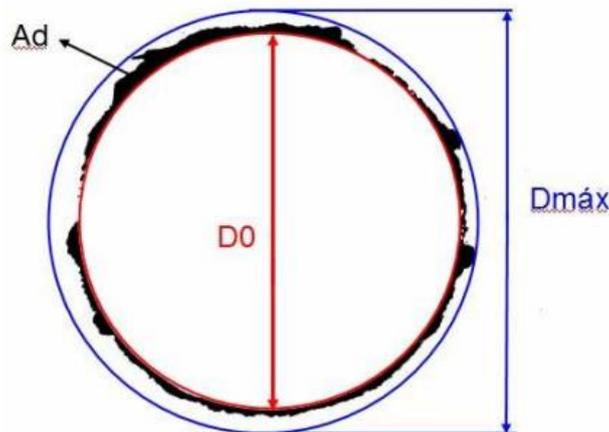
3.0 STATISTICAL COMPARISON

In order to analyze the accuracy of the Taguchi method a full factorial analysis is taken from Silva, (2015), both analyses are shown below.

3.1 Full Factorial

In the full factorial analysis 45 experiments were conducted, for each of these experiments 7 holes were selected at random form the pool of 40 possible holes, and the smallest and largest Fda were excluded from the analysis, after that the value of the 5 remaining samples were averaged. With this a data Figure 8, below is developed.

f (mm)	v_c (m/mim)	118° Fda	118° DP	130° Fda	130° DP	135° Fda	135° DP	140° Fda	140° DP	E-90° Fda	E-90° DP	118° Fda	118° DP	130° Fda	130° DP	135° Fda	135° DP	140° Fda	140° DP	E-90° Fda	E-90° DP
0,08	10	1,17	0,03	1,22	0,03	1,30	0,06	1,21	0,00	1,28	0,01	1,73	0,05	1,73	0,09	1,89	0,07	1,90	0,08	1,88	0,07
0,08	28	1,27	0,03	1,25	0,04	1,32	0,02	1,28	0,04	1,31	0,02	1,84	0,04	1,78	0,05	2,09	0,06	2,17	0,12	1,89	0,08
0,08	57	1,31	0,02	1,24	0,03	1,38	0,01	1,22	0,02	1,21	0,01	3,47	0,16	2,25	0,13	3,07	0,11	2,24	0,11	1,71	0,02
0,15	10	1,27	0,01	1,37	0,01	1,38	0,04	1,38	0,05	1,21	0,02	2,34	0,05	2,29	0,11	2,47	0,27	2,17	0,09	1,82	0,04
0,15	28	1,30	0,02	1,44	0,04	1,40	0,06	1,42	0,02	1,13	0,03	2,44	0,09	2,25	0,14	2,77	0,28	2,67	0,14	1,62	0,01
0,15	57	1,41	0,02	1,47	0,02	1,42	0,02	1,45	0,01	1,17	0,01	3,20	0,16	3,23	0,12	3,05	0,18	2,86	0,18	1,75	0,03
0,30	10	1,56	0,04	1,66	0,02	1,54	0,06	1,69	0,06	1,14	0,02	2,96	0,19	3,14	0,13	2,64	0,30	2,64	0,30	2,14	0,56
0,30	28	1,61	0,06	1,79	0,02	1,65	0,13	1,77	0,08	1,16	0,01	3,61	0,13	2,94	0,06	3,14	0,16	2,86	0,17	2,06	0,08
0,30	57	1,65	0,12	1,87	0,03	1,76	0,09	1,87	0,06	1,18	0,02	3,59	0,04	2,79	0,15	2,76	0,20	3,00	0,06	1,76	0,04
0,08	10	1,21	0,02	1,24	0,04	1,35	0,04	1,25	0,03	1,28	0,04	2,04	0,11	1,92	0,07	2,06	0,06	2,28	0,06	1,92	0,04
0,08	28	1,28	0,02	1,20	0,01	1,40	0,02	1,25	0,03	1,31	0,01	2,19	0,06	2,06	0,06	2,65	0,06	2,50	0,12	1,81	0,04
0,08	57	1,35	0,02	1,67	0,04	1,38	0,02	1,27	0,03	1,25	0,02	2,83	0,02	2,31	0,04	3,11	0,04	2,69	0,11	1,78	0,09
0,15	10	1,34	0,07	1,38	0,02	1,35	0,02	1,35	0,03	1,33	0,03	2,59	0,11	2,09	0,03	2,41	0,07	2,53	0,03	1,88	0,09
0,15	28	1,38	0,01	1,40	0,06	1,33	0,02	1,32	0,05	1,27	0,02	2,33	0,20	2,27	0,10	2,49	0,15	2,76	0,04	1,82	0,12
0,15	57	1,39	0,03	1,37	0,05	1,34	0,03	1,39	0,04	1,23	0,01	2,71	0,12	2,45	0,16	2,79	0,11	2,82	0,12	1,75	0,08
0,30	10	1,55	0,05	1,70	0,06	1,55	0,06	1,58	0,05	1,13	0,02	2,34	0,13	2,35	0,07	2,18	0,24	3,03	0,08	2,01	0,19
0,30	28	1,61	0,06	1,65	0,02	1,57	0,05	1,72	0,06	1,16	0,01	2,84	0,18	2,68	0,08	2,76	0,15	2,99	0,11	1,88	0,11
0,30	57	1,69	0,05	1,75	0,03	1,64	0,01	1,75	0,04	1,17	0,02	2,78	0,10	2,54	0,19	2,61	0,08	3,18	0,15	2,04	0,17

Figure 8. Results for full factorial. Adaptation of Acacio (2015)

3.3 Taguchi

As Taguchi is based in a symmetrical system in which the experiments have the same number of variables for each level an adaptation is needed. In this article, an adaptation of the L9 orthogonal array was used. This array of data was taken as a subset of the completely factorial analysis, and the combination of factors used are expressed in the table 2 bellow. The same combination of factor was used for the [-45°/45°] sheets and compile following the Taguchi method.

Table 2. Taguchi L9 orthogonal array with results of entry and exit for the [0°/90°] sheets.
Average results of 5 specimens. Author (2023)

Experiment [1]	Drill bit	$f\left(\frac{m}{min}\right)$	$V_c\left(\frac{m}{min}\right)$	F_{da} (Entry)	DP (Entry)	F_{da} (Exit)	DP (Exit)
1	118°	0,08	10	1,17	0,03	1,73	0,05
2	130°	0,08	28	1,25	0,04	1,78	0,05
3	135°	0,08	57	1,38	0,01	3,07	0,11
4	140°	0,15	10	1,38	0,05	2,17	0,09
5	E-90°	0,15	28	1,13	0,03	1,62	0,01
6	118°	0,30	57	1,65	0,12	3,59	0,04
7	130°	0,30	10	1,66	0,02	3,14	0,13
8	135°	0,15	28	1,40	0,06	2,77	0,28
9	140°	0,30	57	1,87	0,06	3,00	0,06

4. MAIN EFFECT RESULTS

As a method of analyzing the impact of each variable a main effect graph was develop for each possible analysis, in the graph 1 a comparison between the entry values for Taguchi and factorial is shown, in graph 2 the same analysis is carried but for the exit values.
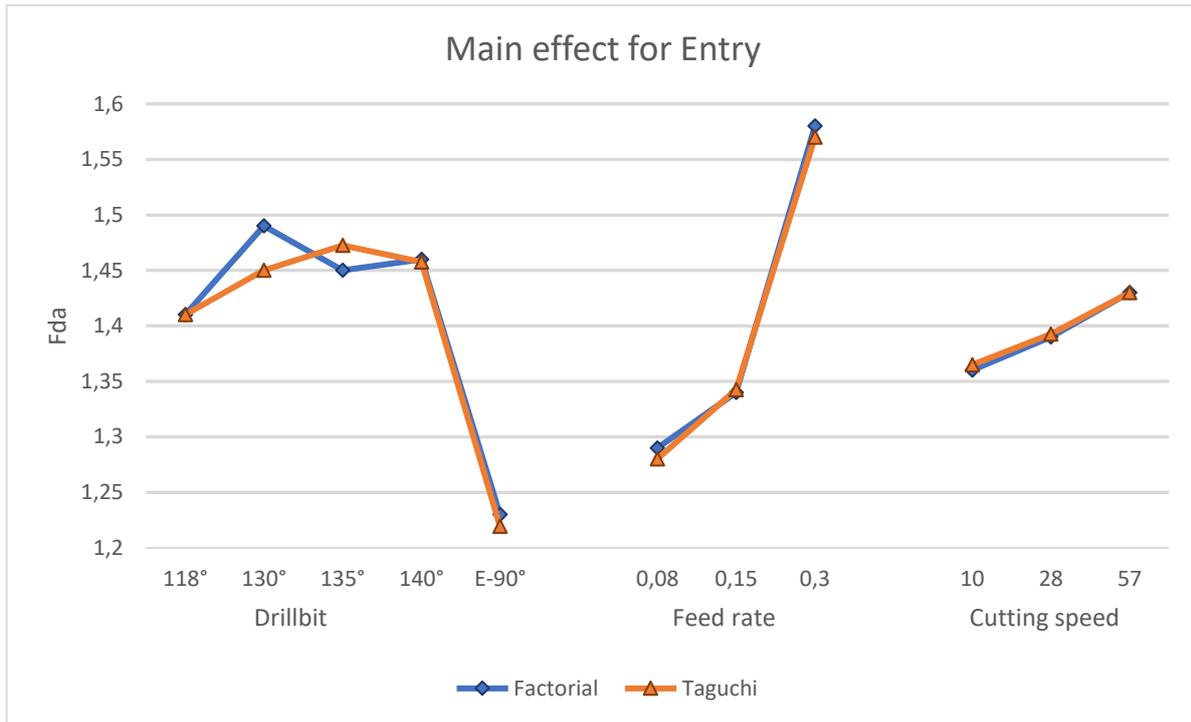
Figure 9. Effects on Entry Fda Author (2023)

In both statistical analysis for the material entry the combination that resulted in the lowest Fda value is the same, that being the E-90° drill bit with a 0,08 mm/rot feed rate and a cutting speed of 10 mm/min. This result is expected since the E-90° drill is design to cut composites.
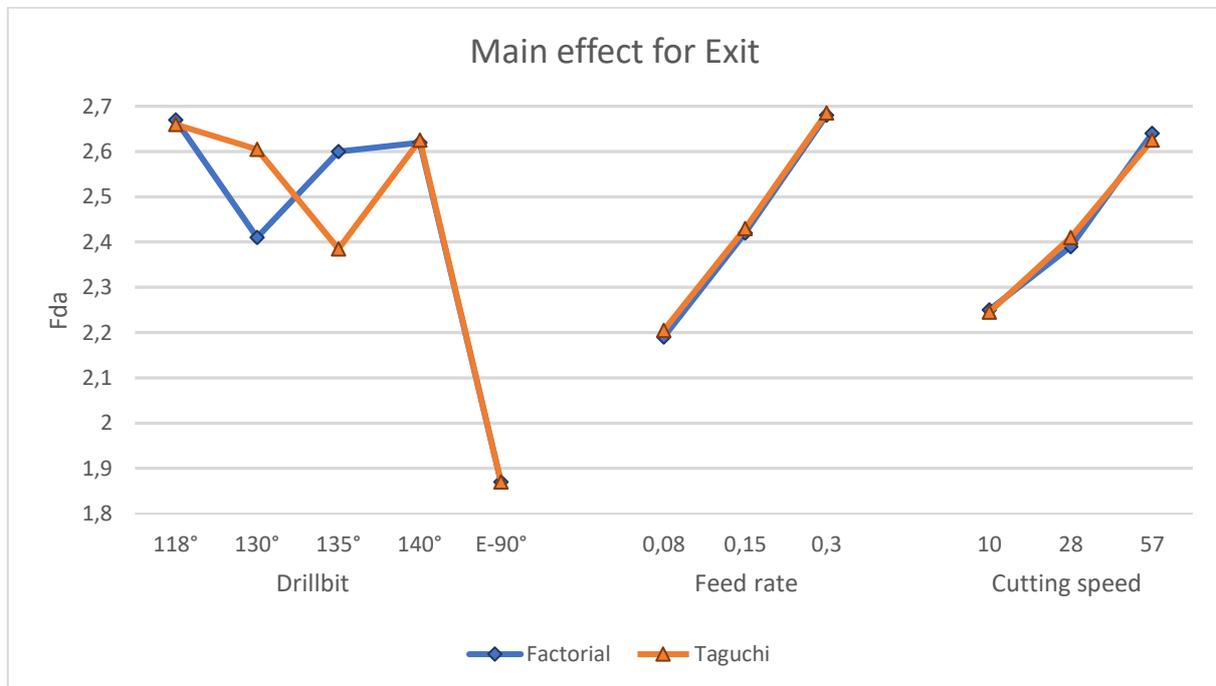

Figure 10. Effects on Exit Fda Author (2023)

For the exit values the same combination of variables as used for the entry resulted in the lowest Fda values, even though both statistical analyses agreed in the combination for the lowest Fda a significant discrepancy is obvious in the 130° and 135° drill bits.

4.1 Full Analysis Comparison

Using the data extracted from the results given in the chapter above an ANOVA analysis was conducted for both methods in all the settings possible, and the data is shown in the Table 3 below.

Table 3. ANOVA Comparison. Author (2023).

Material	Side	Method	Factor	Df	Sum sq	Mean Sq	F Value	Pr(>F)
[0°/90°]	Entry	Factorial	Drillbit	4	2,548	0,6371	49,19	<2e-16
			f	2	4,402	2,2009	169,96	<2e-16
			Vc	2	0,261	0,1307	10,09	6,44E-05
			Residual	216	2,797	0,0129		
		Taguchi	Drillbit	4	0,5096	0,1274	9,401	2,62E-05
			f	2	0,8804	0,4402	32,479	8,69E-09
			Vc	2	0,0523	0,0261	1,929	0,16
			Residual	36	0,4879	0,0136		
	Exit	Factorial	Drillbit	4	23,89	5,972	48,19	<2e-16
			f	2	18,1	9,049	73,03	<2e-16
			Vc	2	8,35	4,175	33,69	1,84E-13
			Residual	216	26,77	0,124		
		Taguchi	Drillbit	4	4,778	1,1944	9,583	2,21E-05
			f	2	3,62	1,8098	14,522	2,38E-05
			Vc	2	1,67	0,835	6,7	0,00336
			Residual	36	4,487	0,1246		
[45°/-45°]	Entry	Factorial	Drillbit	4	1,4594	0,3649	30,702	<2e-16
			f	2	2,701	1,3505	113,643	<2e-16
			Vc	2	0,1347	0,0674	5,669	3,98E-03
			Residual	216	2,5669	0,0119		
		Taguchi	Drillbit	4	0,2919	0,07297	6,067	7,73E-03
			f	2	0,5402	0,2701	32,479	4,66E-07
			Vc	2	0,0269	0,01345	1,929	0,33726
			Residual	36	0,0433	0,01203		
	Exit	Factorial	Drillbit	4	20,304	5,076	114,53	<2e-16
			f	2	2,821	1,411	31,83	7,70E-13
			Vc	2	3,795	1,897	42,81	<2e-16
			Residual	216	9,573	0,044		
		Taguchi	Drillbit	4	4,061	1,0152	25,18	5,28E-10
			f	2	0,564	0,2821	6,997	2,71E-03
			Vc	2	0,759	0,3795	9,411	0,000515
			Residual	36	1,451	0,0403		

To analyze the data values greater than 0.05 are consider not statistically significant. Taguchi neglected feed rates as a meaningful value in the entry for both materials which is a false assumption as the full factorial confirms.

5. CONCLUSION

The Taguchi method help reduce the number of experiments by a factor of 5, which speeds up the process and help on material costs for specimens, and the results for main effect in both analyses agreed on what was the best combination to reduce the Fda.

Even though the Taguchi method helps to reduce the number of experiments in a major way and speed up the process of testing, in both entry of the material [0°/90°] and [45°/-45°] it wrongly assumed that feed rates wasn't an important

factor to analyze which is a false assumption given that the full factorial analysis considers it important. Furthermore, in all main effect analysis the values for the Fda in the 130° and 135° drill bits deviated in a major way, reaching over 0.2 points which is not acceptable.

This big discrepancies in data can be attributed to the massive reduction in data set needed to construct the analysis. So, to correct this a different adaptation of the Taguchi can be used, a array of L15 in which the reduction goes to 3 times may yield a more accurate result.

6. ACKNOWLEDGEMENTS

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