PARAMETRIC STUDIES ON Q-SWITCHED ND:YAG LASER CUTTING OF CFRP THIN SHEETS

C. Leone[1], V. Lopresto[1], I. De Iorio[2]

[1] Dept. of Materials and Production Engineering - University of Naples "Federico II"
P.le Tecchio, 80, 80125 Naples, Italy
claleone@unina.it , lopresto@unina.it
[2] Dept. of Aerospace Engineering - University of Naples "Federico II"
P.le Tecchio, 80, 80125 Naples, Italy
isadeior@unina.it

ABSTRACT

In the present work, the selection of the optimum process parameter during the cutting operation of a carbon fibre reinforced polymer (CFRP) thin sheet using a Q-switched diode pumped Nd:YAG laser and multi-passes laser scan technique is investigated. Parameters like pulse frequency, cutting speed, diode current and scanning number necessary to cut the sheet, also called repetitions, were examined. First, in order to obtain the process effectiveness and the best combination of cutting parameters conditions, marking tests were performed verifying the depth and the width of the grove, for each cutting condition. The optimisation of the process parameters was done using the analysis of variance (ANOVA) that clearly revealed the effect of the single parameters on the grove geometry. The data were also analyzed using three way interaction plots. At last, for the optimum selected parameters, cutting tests were performed considering the number of repetitions necessary to completely cut the laminate, the kerf width and the taper angle. Moreover, optical microscopy analysis was done in order to evaluate the heat-affected zone (HAZ). It is resulted that an accurate selection of the process parameters allows a substantial reduction of the number of repetitions and a limited kerf width.

1. INTRODUCTION

Carbon Fibre Reinforced Plastic (CFRP) materials are generally used for structural applications in different fields as aerospace, structural engineering, F1 and sport equipments, thanks to their high performances. The high tech material image of CFRP and their continuous costs decreasing have produced an increase of their application also in fields like jewellery, watch manufacturing and gift goods where, instead of mechanical properties, sportive, luxurious, and exclusive images are required. In these fields, very thin laminates were cut in complex shape and used to enrich the goods.

Cutting and drilling of CFRP composites with conventional cutting methods produces tool wear, damage such as delamination and fibre pull out [1,2]. Moreover they are not good for very small complex shape. Laser cutting represents a possible alternative: it does not involve any mechanical cutting forces and tool wear thanks to the small spot laser beam that allow to realize complex shape. However, laser cutting is based on the interaction between laser beam and the composites, that produce thermal damage that can decrease the cutting quality if wrong working parameters are adopted [3–8].

Aim of this work was to study the features and the performance of a 20 W nanoseconds Q-switched diode pumped Nd:YAG laser in cutting thin CFRP laminates adopting multi-passes laser scan technique.

Q-switched pulsed pumped Nd:YAG laser is characterized by low power, max 100 W, and short or ultra short pulses with pulse duration from nanosecond to femtosecond. The result is the possibility of the source to produce high pulse power in very short

time. For this reason, it is commonly used in processes like marking, scribing, selective ablations and engraving on metallic, ceramic and polymeric materials where rapid melting and ablation are the interaction modes [9-13]. This laser can be also used in cutting operations: in this case the absence of a cutting head and the low pulse energy allow to remove only small amounts of material in a single laser scan, so, the final cut is generally obtained by a multi-passes laser scan [12].
The use of both high pulse power and short very short time, in theory, could allow a rapid vaporisation of both the matrix and the fibres in the CFRP, reducing the heat transmission effect and the following damages. In practice the short dept of field, the beam inclinations due to the galvanometric scansion system and the beam attenuation effect due to the absorption phenomena during the grove formation [14], do not allow to cut thick laminates. For these reasons, this laser will be only used for thin sheets cut.
In a Q-Switched Nd:YAG nanosecond laser, for given maximum output power, a high pulse repetition frequency causes low pulse energy, low removal rates and low HAZ, that results in a good cut surface quality. On the other hand, low pulse repetition frequency induces high pulse energy, high cutting speed but an increase of the HAZ extension. Consequently, the right process parameters will be a compromise between cut quality and productivity requirements. It results that it is very important to choose optimized process parameters like, pulse repetition frequency, scanning speed and beam power according to the productivity and the required surface quality.
In this work, the selection of the optimum process parameters during cutting operation of a carbon fibre reinforced polymer (CFRP) thin sheets (0.5 ÷0.45 mm thickness), using a nanosecond Q-switched diode pumped Nd:YAG laser, is investigated. The multi-passes scanning techniques was adopted. The examined parameters were the repetition pulse frequency, the cutting speed, the diode current and the scanning number necessary to cut the sheet.
First, in order to obtain the process effectiveness and the better combination of cutting parameters condition, engraving tests were performed verifying the depth and the width of the grove, for each cutting condition. It allows the lower number of repetitions. The process parameters optimisation was done with the analysis of variance (ANOVA) that clearly revealed the effect of the single parameters on the grove geometry. The data were also analyzed using three way interaction plots.
Then, for the optimum selected parameters, cutting tests were performed considering the number of repetitions necessary to completely cut the laminate, the kerf width and the taper angle. Moreover, microscopic analysis were carried out in order to evaluate the heat-affected zone (HAZ). It is resulted that an accurate selection of the process parameters allows a substantial reduction of the number of repetitions necessary to completely cut the laminate and a reduction of the kerf width. These conditions allow to obtain very small complex shape.

2. EQUIPMENT, MATERIALS AND EXPERIMENTAL PROCEDURES

An industrial Q-switched diode pumped Nd:YAG laser (Fly 20 from LASIT), at the fundamental wavelength λ=1064 nm, was used in the experiments. This laser is characterized by a pulses duration of about 150 ns, pulse repetition frequency up to 35 kHz, single pulse energy up to 4.5 mJ and a beam quality factors $M^2 > 12$ (multimode). In the laser head the beam was first expanded, then directed towards two galvanometer mirrors (which determined the feature geometry to be produced) and finally focused by a “flat field” lens with a focal length of 160 mm onto the work piece. The focused beam

diameter, indicated by the manufacturer, is about 160 μm. This kind of laser system is widely used in industrial production for the marking and the micro processing of materials [11].
The laser is controlled through a PC by means of a customized software which allows the generation of the geometric patterns to be cut and the control of the working parameters. These parameters are: diode current used to generate laser beam (A); pulse frequency (F); scanning speed of laser beam (V). The average power (Pm) and the pulse energy (Ep) are related to the diode current and the pulse frequency, as reported in figures 1 and 2 respectively. In the figures the average power is experimentally measured and the pulse energy is calculated as average power/pulse frequency ratio.
Figures 1 and 2 show that an increase of the frequency corresponds to an increase of the mean power and a decrease of the pulse energy. Obviously, an increase of the diode current involves an increase of both the quantity average power and pulse energy. For this reason the influence of both parameters on interaction phenomena are expected.
Rectangular CFRP sheets 500x700 mm^2 and 400 μm in thickness were autoclave fabricated curing at 180°C and 6 bar overlapping two plies of 0/90 fabric BMS 8-276 St. 6K PW-70 Toray Carbon fibre pre-pregs. After curing, rectangular specimens 50x150 mm^2 in plane were obtained by mechanical cutting.
In the first phase, in order to evaluate the influence of the process parameters on the cutting speed and cut geometry, incomplete cuts were performed on the specimens by means of multiple laser beam scanning changing the working parameters. The groove were obtained changing the diode current between two different values of 45 and 55 ampere, the pulse frequency from 2 to 10 KHz with increments of 2 kHz, the scanning velocity at the values of 50 and 100 mm/s. In order to obtain an adequate groove depth, the laser scansion was performed three times in the same conditions. After the experimental tests, the grove geometry was analysed by optical microscopy.
The parameter analysed were the maximum groove width and the groove dept. The experimental data were statistically treated using ANOVA at the aim to better appreciate the influence of the analysed parameters. In table I, the matrix of the experimental tests was reported. From the first phase, the most promising working conditions were obtained in terms of defect and groove depth.
In the second stage, the selected working conditions were used to perform cutting tests in order to quantify the scansion numbers (repetition) necessary to obtain a complete cut. In this case the maximum groove width, the taper angle and the repetition number necessary to for a complete lamina cutting were acquired and analysed. In table II the matrix of the experimental tests used in the second phase was shown.

Table I: Matrix of the experimental tests used for the marking experimental.

Diode current (A)	**Scanning speed (mm/s)**	**Pulse frequency (kHz)**	**Repetition**	**No. of samples**
45 and 55	50 and 100	2; 4; 6; 8 and 10	3	10

Table II: Matrix of the experimental tests used for the cutting experimental.

Diode current (A)	**Scanning speed (mm/s)**	**Pulse frequency (kHz)**	**Repetition**	**No. of samples**
45 and 55	50 and 100	6 and 8	Up to a complete cut	10

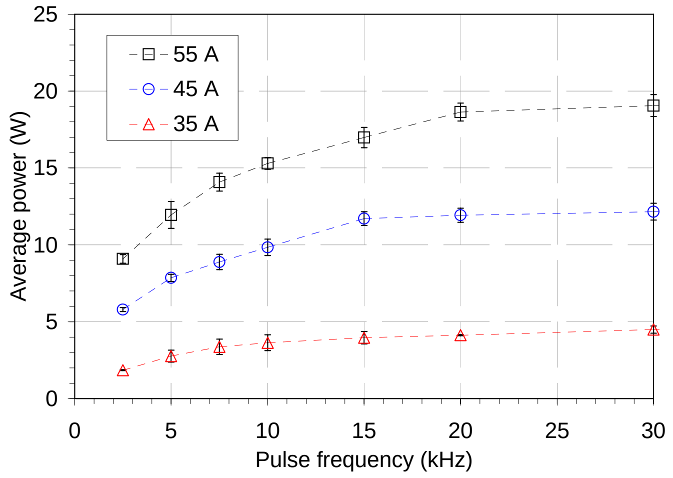

Figure 1: Measured average beam power as a function of pulse repetition frequency, for different diode current.

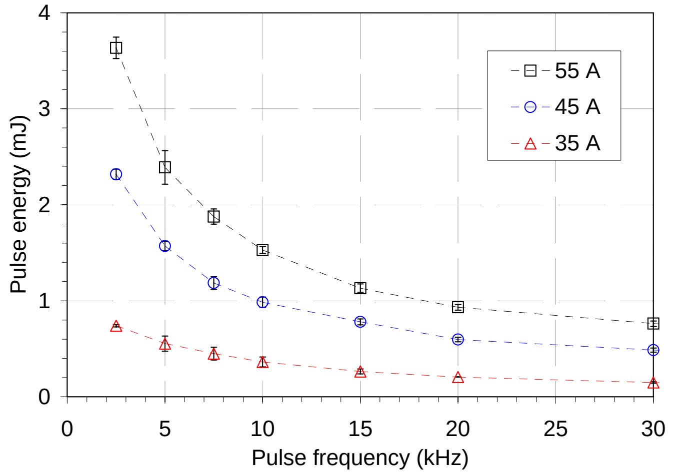

Figure 2: Pulse energy as a function of pulse frequency, for different diode current.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Results and discussion about marking experimental results

The experimental data were statistically treated using ANOVA with the aim to better appreciate the influence of the parameters analysed. The ANOVA table decomposes the variability of the groove geometries into the contributions due to the various factors (A: diode current; B: pulse frequency; C scanning speed; AB: interaction diode current-pulse frequency; AC: interaction diode current-scanning speed; BC: interaction scanning speed-pulse frequency; ABC: interaction diode current-pulse frequency-scanning speed). In the ANOVA table, the Sum of Squares (SS) indicates the contribution of each of the factors considered when the effects of all other factors are removed. Df is the degree of freedom, that is defined to be 1 less than the number of levels for the variables. The Mean Square (MS) is the SS/Df ratio: it has similar meaning of the Sum of Squares, but it shows the variable effect in amplified way. The F-ratio is the ratio MSfactor/MSerror; this parameter is used to compare the variance due to the factor to the variance due to the experimental error. The P-values gives the statistical significance of each of the factors. When the P-value is less than 0.05, the factor has a statistical significant effect on the material property at the 95 % confidence level, [15, 16 and 17].

From Table III, the dept of the groove is significantly influenced by the variables: frequency and scanning speed. In fact both of these variables exhibit a significant F-ratio and P-value less than 0.05. In particular, the influence of the scanning speed is more pronounced than that of the frequency, as the F-ratio value signals clearly.

Obviously, the contributions due to the interaction are clearly visible when the two variables are present together, as visible in B-C and A-B-C interaction rows.

Looking at the groove width (Table IV), the frequency is the only variable exhibits a P-value less than 0.05. The other parameters, speed and diode current, do not seems to influence the width variation. The previous conclusions indicate that the groove geometry depends on the frequency and the scanning speed. It results strange that, despite the increase of pulse energy obtained for the diode from 45 to 55 ampere, the ANOVA does not show any dependence on the diode current.

Table III: Results of ANOVA for the depth on first experimental sets data.

Source	**Sum of Square**	**Df**	**Mean Square**	**F-ratio**	**P-Value**
Diode current **(A)**	0.00444903	1	0.00444903	3.10	0.0801
Frequency **(B)**	0.08875	4	0.0221875	15.45	0.0000
Scanning speed **(C)**	0.132713	1	0.132713	92.42	0.0000
Interaction					
A-B	0.00578836	4	0.00144709	1.01	0.4048
A-C	0.00363141	1	0.00363141	2.53	0.1135
B-C	0.0173597	4	0.00433993	3.02	0.0192
A-B-C	0.018966	4	0.0047415	3.30	0.0122
Residual	0.258463	180	0.00143591		
Total (corrected)	0.53012				

Table IV: Results of ANOVA for the groove width on first experimental sets data.

Source	**Sum of Square**	**Df**	**Mean Square**	**F-ratio**	**P-Value**
Diode current **(A)**	0.00034872	1	0.00034872	0.04	0.8371
Frequency **(B)**	0.100409	4	0.0251022	3.05	0.0183
Scanning speed **(C)**	0.304225	1	0.304225	3.70	0.0561
Interaction					
A-B	0.075899	4	0.0189747	2.31	0.0600
A-C	0.0079294	1	0.0079294	0.96	0.3276
B-C	0.0911256	4	0.0227814	2.77	0.0288
A-B-C	0.090717	4	0.0226792	2.76	0.0294
Residual	1.48114	180	0.00822853		
Total (corrected)	1.87799				

In order to individuate the working conditions able to reduce the cutting time and to obtain the smaller kerf width at the same time, three way interaction plots were performed for the depth and the groove width. They are reported in figures 3 and 4 respectively. From figure 3, the parameters combination that allow the highest depth with only three repetitions, corresponds to a frequency interval 6 to 10 kHz, where the maximum depth are achieved, and to a scanning speed of 50 mm/s. On the other side, from figure 4, the condition that allow the smaller kerf width corresponds to a frequency interval from 4 to 8 kHz, and to a scanning speed of 100 mm/s.

To perform the complete cutting tests, the analysis suggests the adoption of frequency values between 6 ÷ 10 kHz and speed of 50 and 100 mm/s. Besides the difficulty to select an opportune diode current value has advise to use both the diode current values previously adopted.

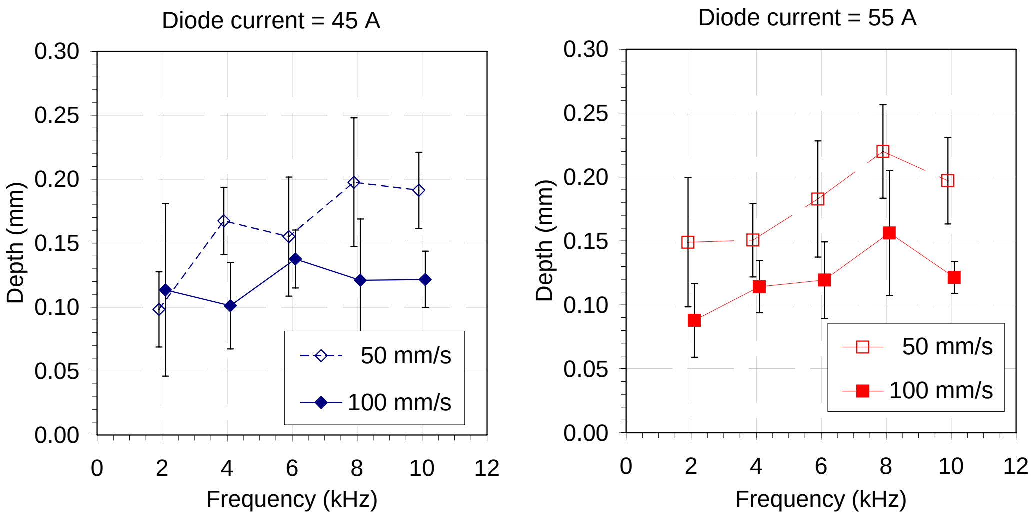

Figure 3: Three way interaction for depth, means and standard deviations value.

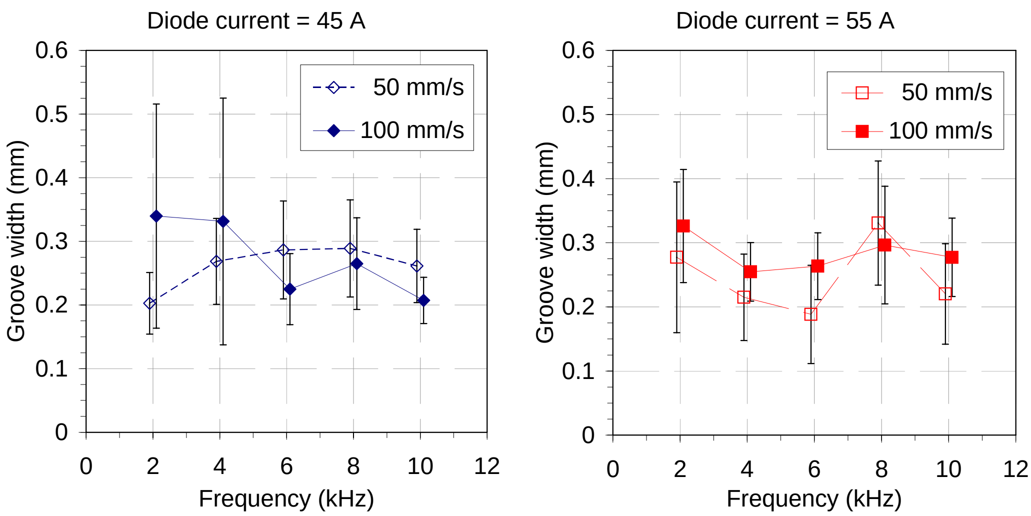

Figure 4: Three way interaction for width, means and standard deviations value.

3.2 Results and discussion about completely cutting experimental results

To evaluate the cutting performance, in table V, the F-ratio and the P-Value obtained by the ANOVA were reported for the three parameters adopted: the repetition numbers

necessary to completely cut the laminates, the top kerf width (measured in correspondence of the laser beam input side) and taper angle.
From Table V, it is possible to note that the repetition number is strongly affected by all the variables, the kerf width is affected by the cutting speed and the taper angle is insensible to the variables.
The ANOVA table decomposes the variability of the groove geometries into the contributions due to the various factors. However do not produce quantitative information about the cut geometries. In order to obtain information on the cut geometry behaviours, the plots of mean were analysed for all the parameters and the parameter interactions. For briefness problems here are reported only the mean value and the standard variation as a function of all the investigated parameters (three way interaction in figures 6, 7 and 8). From figure 5 is evidenced that an increase of the cutting speed produces a substantial increase of the repetition numbers (from a mean value of 11 for s=50 mm/s to 23 for s=100 mm/s). On the contrary, an increase of current produces a decrease of repetition number. In fact, neglecting the other parameter effects, and considering only the mean values, an increase from 45 to 55 ampere produces a decrease of the repetitions from 22 to 13.

Table V: Results of ANOVA for the repetitions on second experimental sets data.

Parameter	**Repetition**		**Kerf width**		**Taper angle**	
Source	**F-ratio**	**P-Value**	**F-ratio**	**P-Value**	**F-ratio**	**P-Value**
Diode current **(A)**	237.31	0.0000	2.72	0.1037	0.32	0.5737
Frequency **(B)**	10.44	0.0019	0.56	0.4581	0.38	0.5393
Speed **(C)**	528.56	0.0000	6.50	0.0129	0.28	0.5959
Interaction						
A-B	31.05	0.0000	3.19	0.0782	2.72	0.1037
A-C	51.32	0.0000	0.04	0.8492	2.88	0.0938
B-C	9.26	0.0033	0.16	0.6911	0.03	0.8556
A-B-C	11.05	0.0014	0.13	0.7167	0.01	0.9340

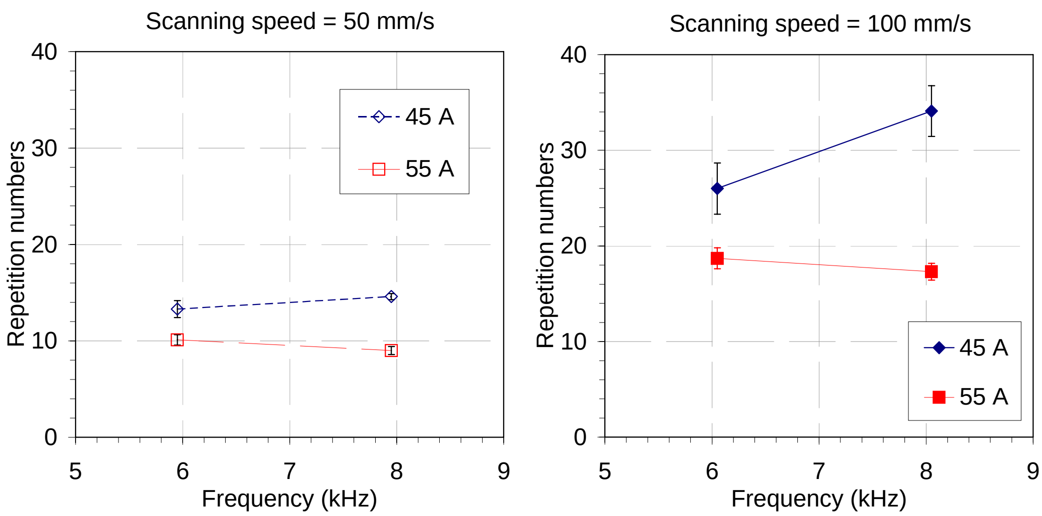

Figure 5: Three way interaction for repetition, means and standard deviations value.

This means that the cutting speed depends on the pulse energy and the mean power.
The effect of the frequency depends on the diode current: for the diode current value set at 45 A, the lowest number of required repetition correspond at a pulse frequency of 6 kHz; on the contrary for a diode current of 55 A, the minimum number of repetition correspond to a pulse frequency of 8 kHz. However, the minimum number of repetitions necessary to completely cut the laminate are 9, that corresponds to a frequency of 8 kHz, a scanning speed of 50 mm/s and a diode current of 55 Amp.
In figure 6, the three way interactions for the top kerf width are reported. Despite the ANOVA indication, a high data scattering and a overlapping of the standard deviation error bars are observable. Also considering ANOVA results, changing the speed from 50 to 100 mm/s, the difference of the mean value of the kerf width, referred to all data, comes from 0.204 to 0.197 mm. This means that in the range of the adopted variables the kerf width does not suffer any variations. A similar conclusion can be obtain for the taper angle behaviours (figure 7).

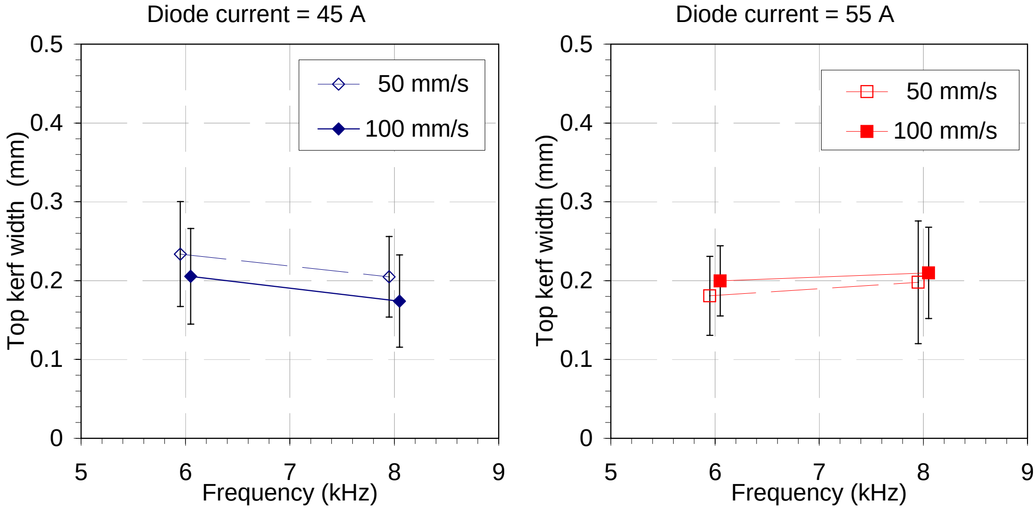

Figure 6: Three way interaction for top kerf width, means and standard deviations value.

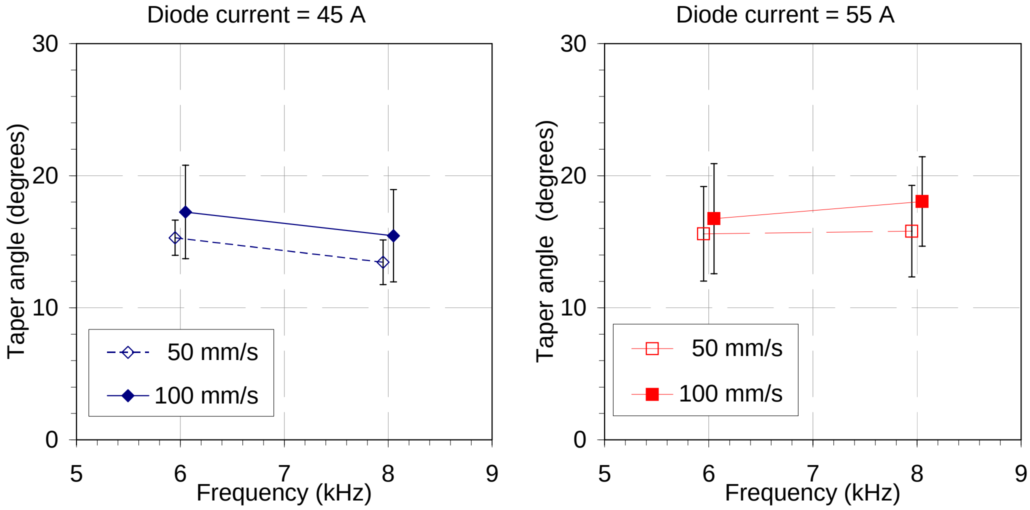

Figure 7: Three way interaction for taper angle, means and standard deviations value.

The microscopic analysis showed absence of internal delaminations and restricted HAZ. The main problem concern the different behaviours of the interaction phenomena fibres occurring changing the position between the fibre and the scanning direction. As examples, in figure 8 the kerf section of two cut samples are reported. As observable, the kerf suffers an enlargement when the beam is moved orthogonally to the fibres. This is evident comparing the two photos. In the left photo, the fibres orthogonal to the beam direction are on the top of image, on the right photo they are in the middle of the laminates. Consequently, in the left laminates the kerf width are larger than in the right one, but the latter shows an increase of the width in the middle.

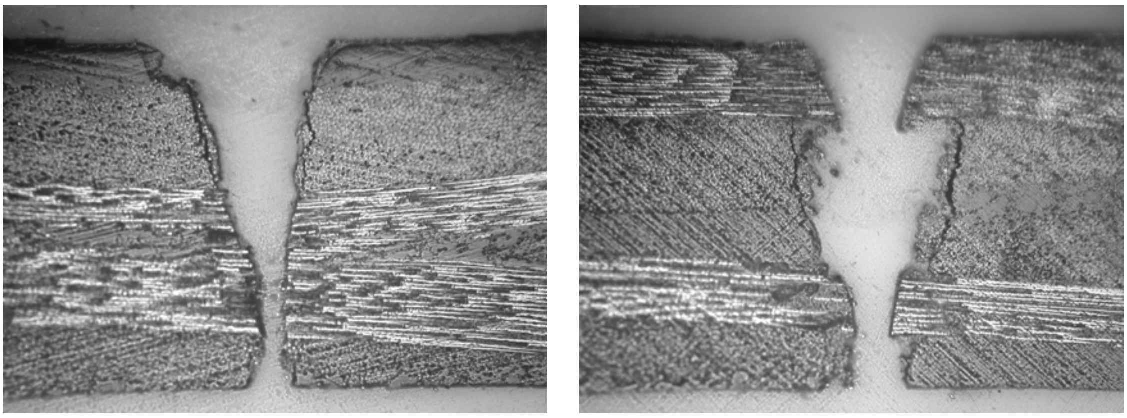

Figure 8: Typical aspect of the laser cut kerf section of two samples.

6. CONCLUSIONS

In this work, a Q-switched Nd:YAG nanosecond laser was used to cutting CFRP laminates 0.4 mm in thickness at the aim to select the best cutting conditions. The analysis of variance was used to select the best cutting conditions in order to reduce working time (the number of repetitions necessary to completely cut the CFRP laminates) and to obtain a good cutting quality, (a narrow width and a low taper angle). From the results, the following main conclusions were drawn:

- Q-switched Nd:YAG nanosecond can be used to cutting thin CFRP laminates in complex shape by means of multi scanning techniques.
- The preliminary tests showed the importance of an accurate selection of the pulse frequency and the scanning speed that play the leading rule for the determination of the cutting speed.
- The cutting tests confirmed the results of the preliminary tests for the cutting speed, it means that the cutting speed depends on the pulse energy and the mean power released by the laser.
- On the other side, the kerf width and the taper angle are unaffected by the working parameters.
- The data scattering of the kerf width and the kerf angle, are due to the materials anisotropy, because of the dependence on the relative position of the fibre axis respect to the beam directions.

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