OPTIMIZING COMPOSITE REPAIRS WITH GREEN LASER

S.Psarras[1], G.Sotiriadis[2], T.Loutas[3] and V.Kostopoulos[4]

[1] Department of Mechanical Engineering and Aeronautics, University of Patras, 26500, Greece, Research Associate, spsarras@upatras.gr and www.aml.mech.upatras.gr
[2] Department of Mechanical Engineering and Aeronautics, University of Patras, 26500, Greece, Research Associate, sotiriad@upatras.gr and www.aml.mech.upatras.gr
[3] Department of Mechanical Engineering and Aeronautics, University of Patras, 26500, Greece, Assistant Proffesor, loutas@upatras.gr and www.aml.mech.upatras.gr
[4] Department of Mechanical Engineering and Aeronautics, University of Patras, 26500, Greece, Proffesor, kostopoulos@upatras.gr and www.aml.mech.upatras.gr

Keywords: Composites, Repairs, Laser, Optimization, Strength

ABSTRACT

In this paper the results of a laser two-layer ablation repair process are analyzed and presented. Such a process is systematically investigated to the direction of identifying the influential parameters as well as optimize their values in a multi-objective optimization task that entails the maximization of the mechanical properties of the repair as well as the material removal rate simultaneously with the minimization of the Heat Affected Zone (HAZ). Quadratic response surface methodologies and Box-Behnken design were utilized to achieve this goal.

1 INTRODUCTION

The repair of aeronautical structures has always been an issue of the highest technological importance for the aviation industry. Common methods for repair involve the mechanical removal of material usually with a hand-held router. Manual scarfing cannot obtain highly precise geometries and requires a highly skilled technician. Also, after the peel-ply removal, the surface is covered with a relatively thick resin film thus, the adhesive binds to this layer and not directly to the fibres which results in a potential weak layer and hinders direct transmission of force into the fibres.

In this study, the developed laser module was envisaged to perform stepped lap material removal on composite plates. Laser processing can support a precise ply-by-ply removal in composite structures and a complex load path optimized geometry is feasible. This way higher ultimate peel stress and interlaminar tension shear strength of the repaired area are anticipated [1-3]. The interaction of the laser with polymer composites can modify the physical and chemical properties of the material through photo-thermal and photo-chemical processes depending on the laser parameters and material properties [4, 5].

2 EXPERIMENTAL SETUP

The experimental setup involved an IPG-GLPN green laser with a mean power of 20 Watt, wavelength at 532 nm, pulse duration <2 nsec and maximum pulse repetition frequency at 600 kHz. A CNC table was used to guide the laser head as well as a special lens with a 150mm focal length was used.

The required parameters for the laser operation were set in an in-house developed National Instruments Virtual Instrument code. In addition, the software allowed different hatching strategies as can be seen in Figure 1. This gave the flexibility of trying them and observe the influence they had on the material removal procedure. An example of the usage of the rectangular spiral can be seen in Figure 2 where a three layer/step scarfing is presented; the initial step window was 50x50mm with a step width of 7.5mm ended in 20x20mm window. In order to remove each layer the number of fifteen passes was needed. Also the hatching distance of 250μm and the average scanning speed of 5m/min resulted in a material removal rate of 1 cm^3/h.

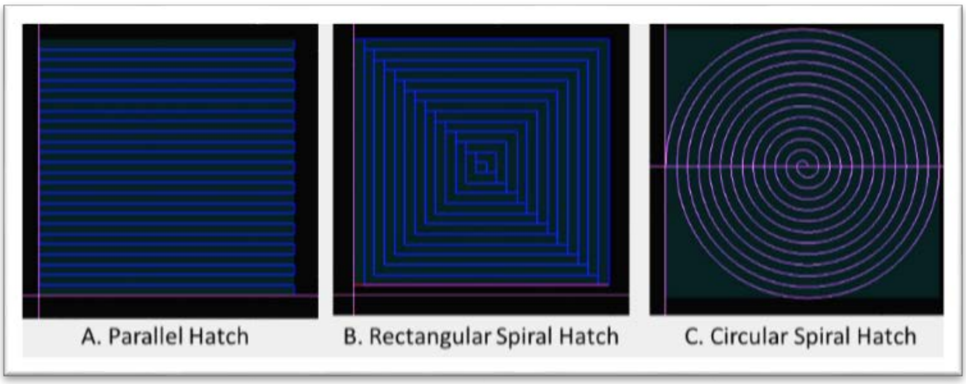

Figure 1: Hatching strategies

Figure 2: An example of step scarfing on a composite sample

3 DESIGN OF EXPERIMENT

A test campaign was necessary in order to identify the influential parameters that affected critical quantities such as the size of the Heat Affected Zone (HAZ) in 3 different areas, the material removal rate (RR) as well as the shear strength (SS) of in-house manufactured CFRP single-lap bonded joints. Operating laser parameters were examined according to two major parameters; the energy density (E.D.) and the hatching dimension vertical to the laser movement D_y. Energy Density is defined as:

$$E.D. = \frac{P_{AVG}}{V_{scan} * d_{spot}} \quad (\mathrm{J/m^2})$$

Where:

P_{AVG} is the average power output of the laser (W)

V_{scan} is the scanning velocity of the laser (m/sec)

d_{spot} is the spot diameter of laser beam on the metal surface (m)

The necessary number of experiments for the quantitative factors was extracted from the Box-Behnken Design [6] for quadratic analysis. 15 runs with 3 middle points are as minimum required. The parametric values that used were a minimum of 1500 mm/min and a maximum of 6000 mm/min for the Vscan (A), a minimum of 300 kHz and a maximum of 600 kHz for pulse frequency (B) and a minimum of 100 mm and a maximum of 250 mm for the Hatching Distance (C).

4 RESULTS

Table 1 summarizes the experimental results after the material ablation, the single-lap tensile tests and the microscopical investigation of the laser-processed areas and especially the boundaries.

Table 1. the Experimental Responses-Results

Run	Removal Rate	Single-lap Shear Strength	HAZ 1st-Step	HAZ Side	HAZ 2nd-Step
	mm^3/min	MPa	µm	µm	µm
1	6,617	23,5	289	730	84
2	2,986	22,695	120	695	95
3	6,018	24,166	257	398	57
4	8,45	23,402	321	886	184
5	7,444	23,36	276	337	105
6	3,834	19,553	298	572	139
7	2,774	26,83	349	268	233
8	7,217	23,806	407	422	37
9	6,515	22,884	206	529	154
10	2,291	23,498	375	712	193
11	10,629	24,102	231	399	124
12	10,129	22,3	278	400	43
13	6,938	22,197	273	302	214
14	5,003	28,779	236	327	229

.

The illustrations in Figure 3 and Figure 4 show the 3-dimensional diagrams of the responses of the factor pairs. The third factor each time gets the two possible extremes, (-1) low and (+1) high. These data are useful because the joint effects of both main variables on the respective responses are simultaneously evaluated.

The Response Surfaces for Removal Rate are presented in Figure 3 as follows:

1. Figure 3 (a)-(b) presents the effects of combination of factors (A) and (B) in responses, using the (C) factor two values per response:
    - Low: (-1) ~ 100µm
    - High: (+1) ~ 250µm

2. Figure 3 (c)-(d), the effects of combination of factors (A) and (C) in responses, using two values of factor (B) per response:
    - Low: (-1) ~ 300kHz
    - High: (+1) ~ 600kHz

3. Figure 3 (e)-(f), presents the effects of combination of factors (B) and (C) in responses using two values of factor (A) per response:
    - Low: (-1) ~ 1500mm / min
    - High: (+1) ~ 6000mm / min

In the same pattern, the Response Surfaces for HAZ are presented in Figure 4.

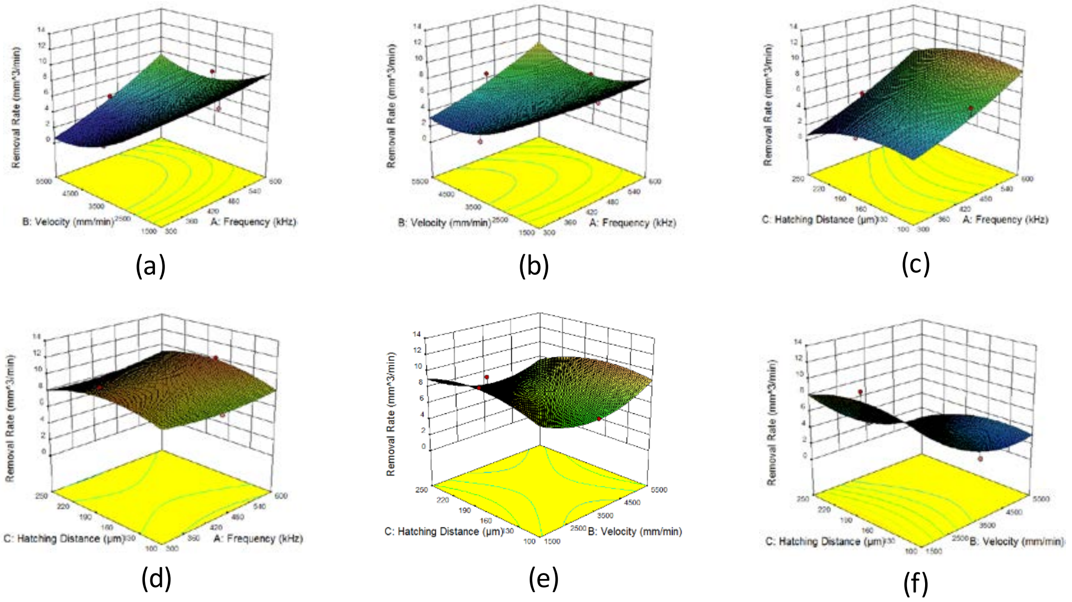

Figure 3. The Response Surfaces for Removal Rate

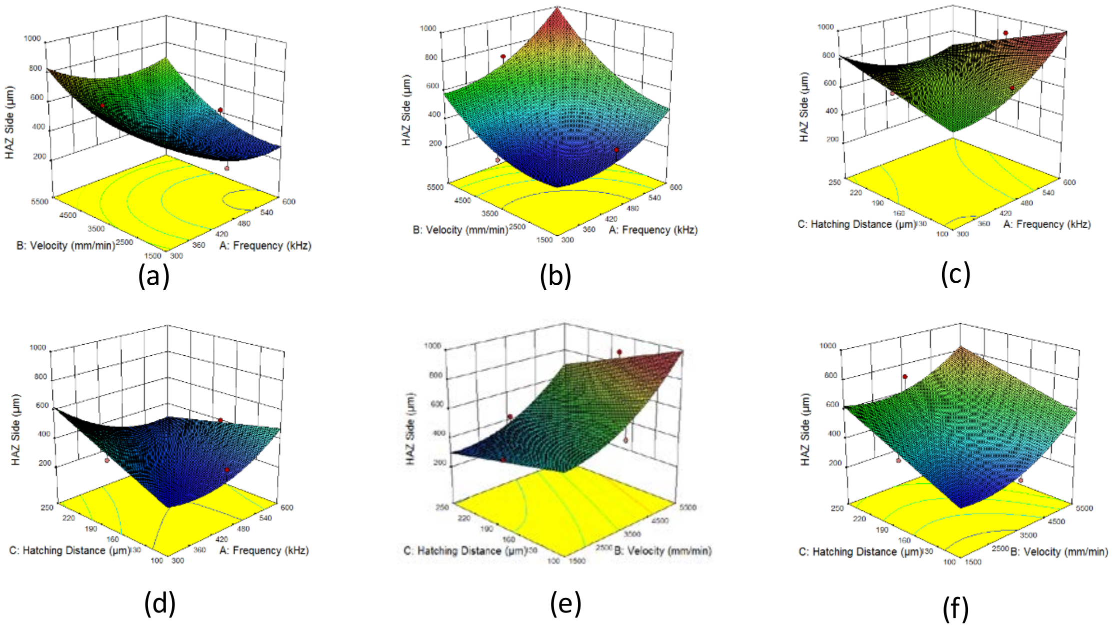

Figure 4. The Response Surfaces for HAZ

From the above diagrams, it can be concluded that the optimal settings to achieve an increase in Shear Strength and Material Removal Rate and a reduction in HAZ are as follows:

- Speed: 1500 mm / min
- Frequency: 456.212 kHz
- Distance Between Scans: 145.005 µm

The above settings result in the following values for the features:

- Material Removal Rate: 8.576 mm3 / min
- Shear Strength: 26.24 MPa
- First Step HAZ: 0.239 mm

- Side HAZ 0.334 mm
- Second Step HAZ: 0.087 mm

Table 2 ANOVA Dispersion Analysis for removal rate

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	81,27	9	9,03	6,07	0,0305	significant
A-Frequency	*23,23*	*1*	*23,23*	*15,63*	*0,0108*	
B-Velocity	*21,96*	*1*	*21,96*	*14,77*	*0,0121*	
C-Hatching Distance	*1,18*	*1*	*1,18*	*0,79*	*0,4141*	
AB	*8,89*	*1*	*8,89*	*5,98*	*0,0582*	
AC	*0,35*	*1*	*0,35*	*0,24*	*0,6475*	
BC	*1,30*	*1*	*1,30*	*0,87*	*0,3933*	
A^2	*1,12*	*1*	*1,12*	*0,75*	*0,4249*	
B^2	*15,67*	*1*	*15,67*	*10,54*	*0,0228*	
C^2	*6,14*	*1*	*6,14*	*4,13*	*0,0978*	
Residual	7,43	5	1,49			
Lack of Fit	*6,89*	*3*	*2,30*	*8,39*	*0,1083*	*not significant*
Pure Error	*0,55*	*2*	*0,27*			
Cor Total	88,70	14				

Table 3 ANOVA Table for HAZ Side

Source	Sum of Squares	df	Mean Square	F-Value	p-value Prob > F	
Model	4,415E+005	9	49059,61	5,32	0,0401	significant
A-Frequency	*3321,13*	*1*	*3321,13*	*0,36*	*0,5745*	
B-Velocity	*2,610E+005*	*1*	*2,610E+005*	*28,32*	*0,0031*	
C-Hatching Distance	*2592,00*	*1*	*2592,00*	*0,28*	*0,6186*	
AB	*9025,00*	*1*	*9025,00*	*0,98*	*0,3679*	
AC	*75900,25*	*1*	*75900,25*	*8,23*	*0,0350*	
BC	*3782,25*	*1*	*3782,25*	*0,41*	*0,5500*	
A^2	*44744,64*	*1*	*44744,64*	*4,85*	*0,0788*	
B^2	*46800,03*	*1*	*46800,03*	*5,08*	*0,0740*	
C^2	*0,41*	*1*	*0,41*	*4,451E-005*	*0,9949*	
Residual	46088,42	5	9217,68			
Lack of Fit	*42987,75*	*3*	*14329,25*	*9,24*	*0,0992*	*not significant*
Pure Error	*3100,67*	*2*	*1550,33*			
Cor Total	4,876E+005	14				

At this stage, to evaluate the effect of these independent variables on the respective reactions, dispersions were analyzed using the Design Expert program according to the BBD model and the results were determined based on a 95% confidence level (P-value = 0 , 05). The significance of each factor for the equation was evaluated according to the probability value (P-value). Significant equation factors should have a probability value greater than 95% (P-value ≤ 0.05) and thus the null hypothesis H0 is discarded while the probability value for non-significant factors will be less than 95 % (P-value ≥ 0.05), which means that these factors should be eliminated by the equation and the final analysis.

The outcome of the subsequent Analysis of Variance – ANOVA for all responses at a confidence level of 95% (p-value = 0.05), was that for the Removal Rate (Table 2) and HAZ Side (Table 3) significant models were obtained with p-values of 0.0305 and 0.0401 respectively.

6 CONCLUSION

From the Analysis, it was observed that the responses affected by this experimental process were the HAZ of the "1st Stage" and the HAZ of the "Side Dept.". The factors that can be considered important for this HAZ 1st Step impact are the combination of Frequency and Distance between Scans and the square of the Distance between Scans factor. For the HAZ Side response, Speed and Frequency, Speed / Frequency-Frequency and Frequency Response are important.

Generally and from the optimization segment it is observed that the Speed remains constant and even at the lowest possible value given to it, while the Frequency Factor that actually represents Power receives a median value. Finally, the Hatching Distance factor gets low, about 30% from the lower end. The near-optimum parameters for a laser process with minimum HAZ, maximum SS and RR as the objective are determined at $f \approx 500$ kHz, $V \approx 1570$ mm/min and $HD \approx 171$ μm as they extracted from the Response Surface Methodology analysis and the obtained models.

ACKNOWLEDGEMENTS

The research leading to the results has received funding from the FET-OPEN Programme of the European Union's H2020 Programme under REA grant agreement N° [665238].

REFERENCES

[1] F. Fischer, S. Kreling, P. Jaschke, M. Frauenhofer, M. Kracht, and K. Dilger, "Laser Surface Pre-Treatment of CFRP for Adhesive Bonding in Consideration of the Absorption Behaviour," *The Journal of Adhesion*, vol. 88:350–363, 2012.

[2] K. Y. Blohowiak, M. N. Watson, Belcher, M. A. E. Castro, J. Baldwin, and S. Koch, "Laser Scarfing For Adhesive Bonded Composite Repairs. Used by the Society of the Advancement of Material and Process Engineering with permission," *Boeing. Education & Green Sky – Materials Technology for a Better World. Proceedings* 2013.

[3] C. Leone, I. Papa, F. Tagliaferri, and V. Lopresto, "Investigation of CFRP laser milling using a 30W Q-switched Yb:YAG fiber laser: Effect of process parameters on removal mechanismsand HAZ formation," *Composites: Part A* vol. 55 129–142 2013.

[4] C. Chan, T. Ko, and H. Hiraoka, "Polymer surface modification by plasmas and photons," *Surface Science Reports*, vol. 24:1–54, 1996.

[5] T. Lippert, "Interaction of photons with polymers: from surface modification to ablation," *Plasma Processes and Polymers* vol. 525–546, 2005.

[6] G. E. P. Box and D. W. Behnken, "Some New Three Level Designs for the Study of Quantitative Variables," *Technometrics*, vol. 2, 1960.