FIBRE LASER MATERIAL PROCESSING OF AEROSPACE COMPOSITES

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Abstract

Laser material processing of composite materials such as carbon fibre reinforced plastics (CFRP) for aerospace structures is generating a great deal of interest in the aerospace industry. The aerospace sector is seeing the potential benefits of laser processing over other machining technologies such as water jet or traditional mechanical cutting or milling. An important question that the industry needs answering is which laser systems offers the best processing characteristics with respect to machined surface quality, cycle time and cost. At present three laser systems are being seriously considered by the industry for applications such as drilling, cutting and milling operations on CFRP. They are Pulsed TEA-CO_2 , DPSS UV and fibre laser systems. This paper investigates laser cutting and laser milling of CFRP and the machining strategy for cutting CFRP and GFRP using a fibre laser.

Introduction

Carbon fibre reinforced plastic (CFRP) composites have attracted considerable interest from a number of different industrial sectors but primary from the aerospace sector. Aircraft manufacturers, such as Boeing and Airbus, see the potential benefits of using CFRP composites due to its superior mechanical properties over its metallic alternatives. Their low density, high strength and high stiffness to weight ratio make them a suitable candidate for many aerospace applications. These new aerospace materials require processing i.e. cutting, drilling and milling normally using traditional machine tools. Recently aerospace companies have been investing in water jet technology for cutting CFRP composites. Water jet can give a high quality cut but this has associated problems of causing delamination and requires a pilot hole to be drilled mechanically if the cutting process starts anywhere other than at the edge of the sheet. Other potential issues with water jet cutting are disposal of waste cutting products. The use of lasers for cutting of CFRP composites has yet to be exploited by the aerospace industry.

Pervious work on laser processing of composite materials can be split into two main themes, firstly laser drilling with a Nd-YAG laser and secondly laser cutting with a CO_2 laser system. One exception to this is Galantucci [1] who investigated laser cutting of a thermoset polyester resin with an excimer laser due to its importance as a matrix material for plastic composites. Galantucci derived a photo ablation model that predicted the cross sectional profile of the cut. Caprino and Tagliaferri [2] derived a one dimensional model that predicted the maximum cutting speed for cutting CFRP as well as other composite materials such as glass fibre reinforced plastic and aramidic fibre reinforced plastic with a CO_2 laser. Two CO_2 laser systems were used in experimental work to verify the model. A 0.5 kW Valfivre L500 and a 2.0 kW BOC system. The material thickness varied from 1.5 mm to 4.5 mm. The model gave good agreement with the three different composites and was expected to work well for high power density and feed rates. Cenna and Mathew [3] developed a model than looked at various parameters in laser cutting, material removal rate, kerf width kerf angle and energy transmitted through the cut kerf. The laser used to verify the model was once again a CO_2 laser, a 1.5 kW PRC. The developed model using the energy balance equation successfully predicted the above parameters for aramidic fibre reinforced plastic but underestimated the results for glass fibre reinforced plastics. Shanmugam et al [4] compared laser cutting with plain water jet and abrasive water jet cutting. The experiments determined the kerf angle and the Ra of the cut surface. A CO_2 laser was used during the experiments but the make or material thickness was used in the experiment was not given. The paper concluded that abrasive water jet cutting was the preferred cutting method. This could well be true for thick CFRP, 10 mm or greater but this threshold has yet to be determined. Cheng et al [5] and Voisey et al [6] identified an interesting phenomena when laser drilling. They observed that depending on the type of fibre used in the composite it could have a tendency to swell during laser drilling. Voisey determined that there was a possible link to impurities contained within the fibre and the rapid temperature gradient induced by laser processing. The high pressure gases act as a driving force leaving the laser processed composite structure more open after laser drilling.

Li et al [7] investigated drilling holes into CFRP using an Avia-X high power Q-switched third-harmonic Nd:YVO_4 diode pumped solid state laser system. Operating at 355 nm he investigated the effects of scanning speed on the cut quality of a matrix of nine holes, 2mm in diameter. The average power for all of his experiments was 10W and the repetition rate was 40kHz. In an attempt to thermally manage the drilling process they stopped drilling after every four pass for 1 ~ 2 seconds to reduce heat accumulation. They found a processing window between 50 mm/sec and 800 mm/sec. The higher the processing speed, better the hole quality. The number of scans needed to drill a hole also increased with scan speed. An interesting idea investigated by Li et al was a drilling strategy for CFRP. The group investigated laser cutting multiply rings, i.e. two or three cutting paths from the inside to the outside of the hole producing a kerf width of either 225 µm or 300 µm for a three ring cutting strategy. This opened the cutting area allowing the plasma plume to escape from the kerf and therefore allowed more of the laser beam to reach the material and lead to a more efficient removal rate.

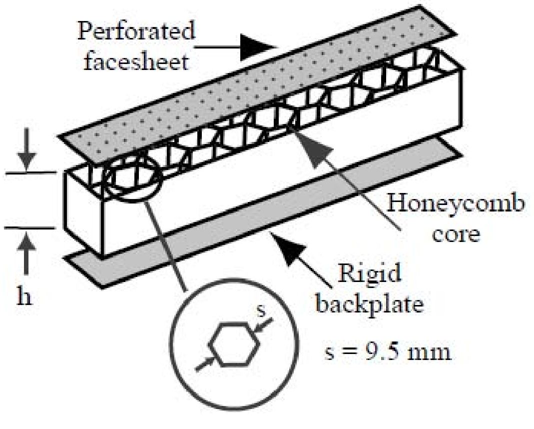

Figure 1. Schematic of an Acoustic Liner [8].

The aerospace industry are particular interested in drilling holes but one particular application where hole drilling is important is in drilling the leading edge of the nacelle to make the surface of the nacelle acoustically absorbent. The acoustic absorbing structure call an acoustic liner, consists of a perforated sheet behind which is a honeycomb structure figure 2. Finally there is a non-porous back sheet. The depth of the honeycomb with the hole diameters in the top sheet, the top sheet thickness and the percentage of the area cover given by the holes decides the frequency response for the acoustic liner. Due to the interest in this technology we have concentrated our efforts on laser drilling of holes either by percussion drilling or laser trepanning (Laser Spiral Drilling) using a scanning head. We explore the drilling/cutting strategy of multiply passes to open up the machined area and the affect of assist gas on the quality of laser percussion drilling of CFRP.

Experimental Setup

The GSI JK200FL fibre laser has a maximum power of 200W and the beam was delivered to the samples via a 10µm core optical fibre. The scanning head is shown in figure 2 the beam was delivered to the work piece using a Cambridge Technology scanning optics and a 100 mm focal length f-theta lens. The focused spot diameter was calculated to be 13 µm and the focus was on the surface of the sample. The JK200FL was used to investigate laser cutting of CFRP.

The other laser system used in this investigation was the GSI JK300D drilling laser. It has a peak power of 16 kW and is delivered through a 300 µm optical fibre. The optical set up gave a spot size of 300 µm. The focal positions of both the JK200FL and the JK300D were focused on the surface. The JK200FL operated in both continuous and modulated mode. The JK300D was used in percussion drilling mode. An assist gas was also used with the JK300D, nitrogen and carbon dioxide. Only one gas pressure was used during the investigated for both gases which was 5 bar.

The composite materials used in this study were pre-impregnated (“pre-preg”) material; a stitched carbon toughened epoxy resin 5 harness satin weave MTM44-1. Resin Film Infusion 2 ply with peel ply, Carbon fibre pre-preg 1 ply with peel ply. Carbon fibre pre-preg, 2 ply with peel ply. 8552 glass fibre reinforced plastic. The sample thicknesses varied from 330 µm to 1.13 mm.

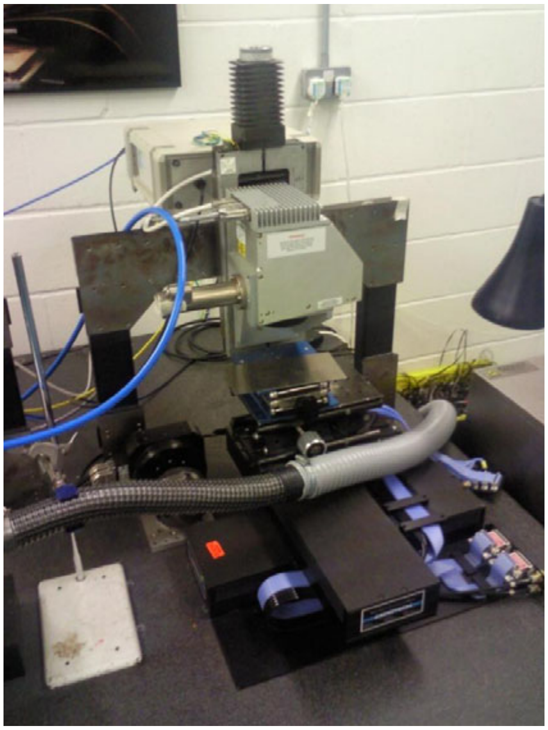

Figure 2 JK200FL Laser Set-up

Results

Two different drilling techniques was investigated, (1) percussion drilling with the JK300D and (2) laser spiral drilling using the JK200FL and scanning optics.

Laser Percussion Drilling

Table 1 gives the pulse parameters for the JK300D. Two different assist gases were used in this particular study Nitrogen and Carbon Dioxide. Figure 3 shows the surface condition of laser machined CFRP that hasn’t been post processed.

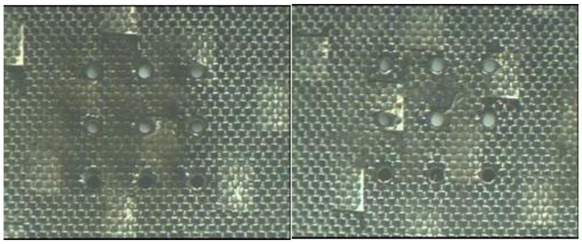

Figure 3 Surface contamination of a N2 and CO2 assist gas drilled CFRP.

CFRP that had been laser percussion drilled using nitrogen as an assist gas always show signs of surface debris in the form of a fine layer of particles. This material we believe is remnants of the polymer matrix that had thermally decomposed and had settled on to the surface of the CFRP sample. On the other hand laser processing with CO_2 assist gas show no or very little sign of the surface contamination. We believe that the CO_2 assist gas has superior cooling qualities over N_2 with respect to laser processing of CFRP. An explanation to why CO_2 gives a better cooling result is we believe due to the Joules-Thomson effect. The rate of change of temperature with respect to pressure in a Joule-Thomson process is μ_{JT}. The value of μ_{JT} the Joules-Thomson coefficient is expressed in K/Pa in SI units and expresses the following relationship.

Table 1

Pulse width (ms)	Pulse energy (J)	Peak power (kW)	Average power (W)	Pulse frequency (Hz)	No of shots
0.3	3.6	12	81	22.4	2
0.3	3	10	67	22.4	2
0.3	2.4	8	54	22.4	3
0.3	1.8	6	40	22.4	5
0.3	3.6	12	161	44.8	2
0.3	2.4	8	108	44.8	3
0.5	6	12	134	22.4	2
0.5	5	10	112	22.4	2
0.5	4	8	90	22.4	3
0.5	3	6	67	22.4	5
0.5	3	6	134	44.8	5

$$— \qquad (1)$$

At low temperatures the intermolecular forces between the molecules are attractive. When the cold gas expands the average distance between the molecules increase. This means that the molecules are pulled apart. Since they attract each other this separation of the molecules will take energy. For an adiabatic process the only source of energy is the internal energy of the gas itself so with the internal energy reduced, the gas cools. Figure 4 shows a plot of the Joules-Thomson coefficient for argon, nitrogen and carbon dioxide.

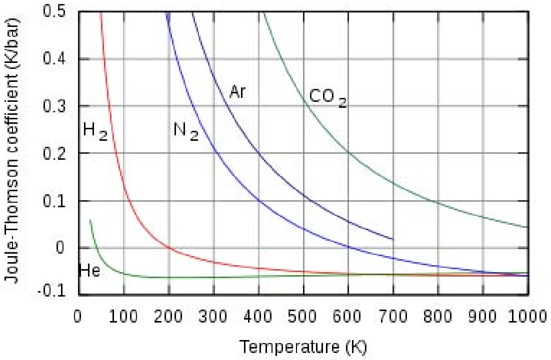

Figure 4 Plot of the Joules-Thomson Coefficient [9]

Figure 5 and 6 shows SEM images of holes percussion drilled using both N_2 and CO_2 assist gas at 5 bar.

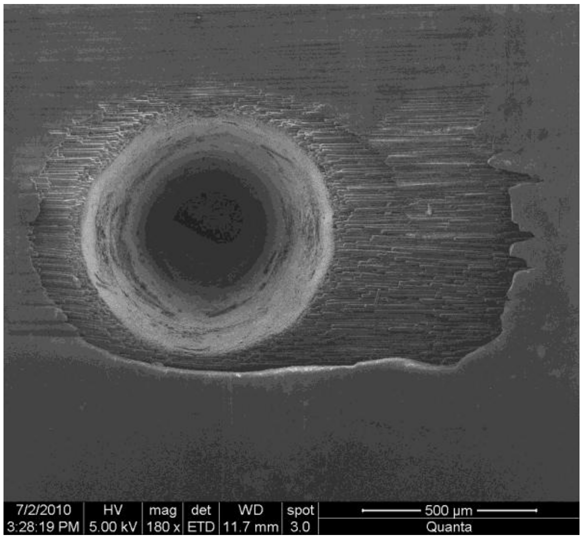

Figure 5 Laser percussion drilled hole, assist gas CO_2 pulse width 0.3 ms

The general appearance in the image shows some surface disruption of the upper layer of the fibres for both types of assist gas. This could be due to the plasma plume reradiating and causing surface damage. This leads us to believe that the surface contamination is due to material being removed from the holes interior and this is borne out by graphs in figure 7 and 8.

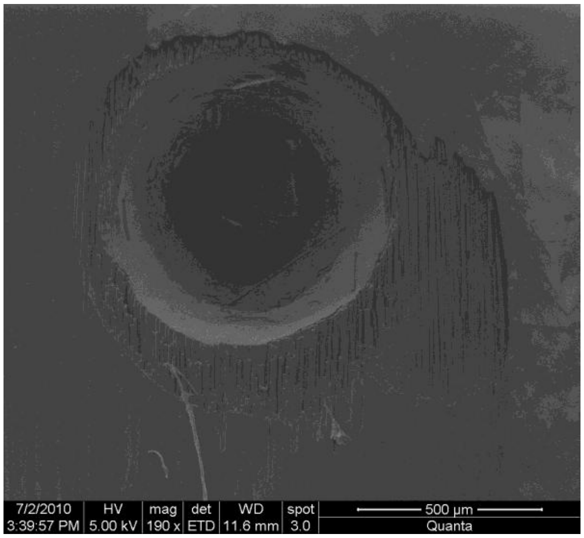

Figure 6 Laser percussion drilled hole, assist gas N_2 pulse width 0.3 ms

Figure 7 shows the distribution of hole entrance diameters for the two different assist gases N2 and CO_2 and at different pulse energies. The graph shows the general tread of drilling CFRP with N_2 and CO_2. The N_2 assisted holes have a larger diameter than holes drilled with CO_2.

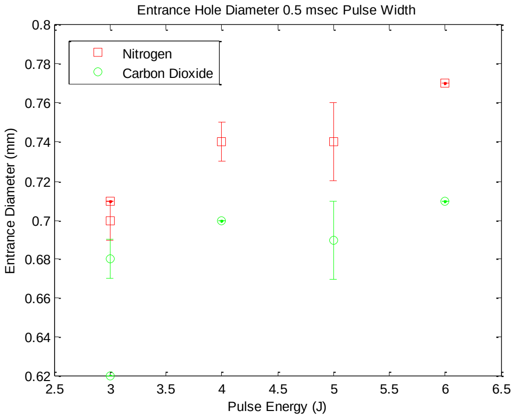

Figure 7 Graph showing the distribution of entrance hole diameter for assist gases N_2 and CO_2

Figure 8 also shows that less material is removed with CO_2 used as an assist gas than N_2. The taper values for holes drilled CO_2 are greater than holes drilled with N_2.

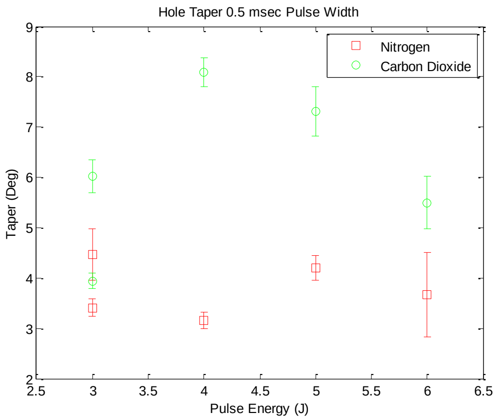

Figure 8 Graph showing the distribution of hole taper for assist gases N_2 and CO_2

Laser Spiral Drilling

Using the set up in figure 2 we used the JK200FL fibre laser to trepan a matrix of 2 mm diameter holes on a variety of different composite materials. Past experience of cutting CFRP has shown us that trying to cut the material as if it were a metal fails to produce a satisfactory cut for composites over thicknesses of 1.0 mm. It became obvious that what was needed was a larger kerf width that would allow material to escape the kerf without matrix adhering to the freshly cut face and stopping slug of material falling out. The cutting strategy we devised is presented in figure 9.

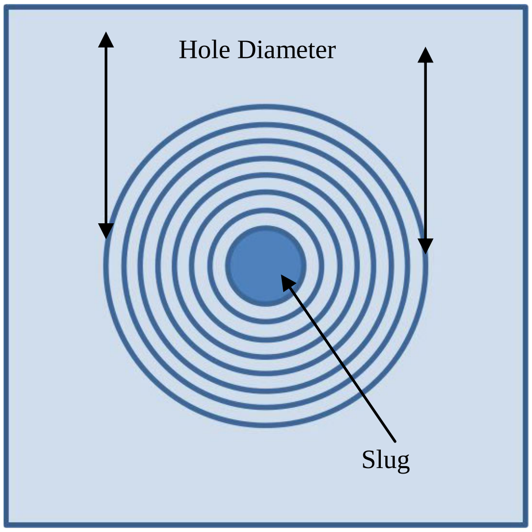

Figure 9 Scanning strategy for drilling CFRP.

Each ring is an individual scan path for the laser beam. The central dark area is the central slug of material that will fall out as soon as the hole has been cut. In these particular experiments the diameter of the central slug was 1 mm in diameter, with the outer ring the hole final diameter 2 mm. The distance between the individual rings was either 200 µm or 300 µm. Figure 10 shows a partial drilled-machined hole which gives shows the drilling mechanism.

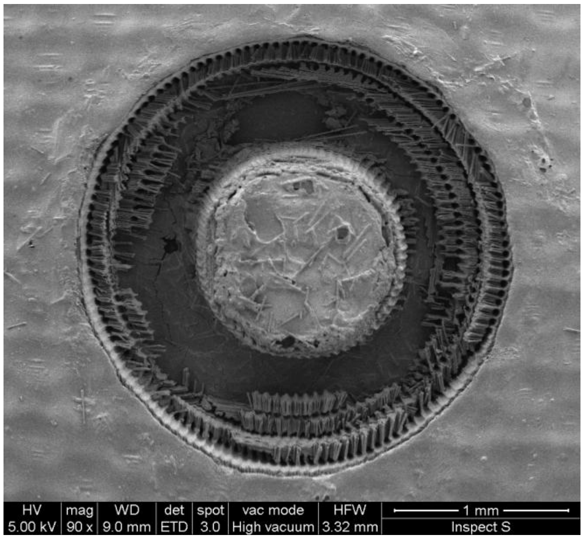

Figure 10. Image showing a partial drilled hole.

Compared with figure 9 you can see the last 3 outer cutting paths of the laser with the individual witness marks of the pulses. The slug is still sitting in the centre of the hole. The laser parameters used to machine this holes was with the JK200FL in a modulation mode, 50µsec, pulse energy 10 mJ, peak power 100%, 10% duty cycle, frequency 2 kHz, average power 18 W. Figure 11 shows a magnified view of the lower portion of the hole in figure 10 and shows the mechanism of material removal. The image shows that the fibres are cut into bundles of short lengths of fibres. Isolating the fibres in this way means heat builds up in the bundles removing the polymer matrix material through the mechanism of conduction along the short fibre lengths, In this particular example the fibre bundle lengths was 200 µm. The short bundles of fibres are then ejected with the vaporised polymer material.

The edge quality on the top surface of a laser spiral drilled hole tends to show less thermal damage than a hole cut in a more traditional laser processing technique. Figure 10 and figure 11 shows the extent of thermal damage on the surface of the CFRP sample. The amount of burn back on the top surface is only a few tens of microns. The authors believe that this damage is caused by the plasma plume that is created during the drilling process. The speed of laser processing with a scanning optic and the open architecture of the holes geometry reduces the damage to the matrix material on the surface of the CFRP sample.

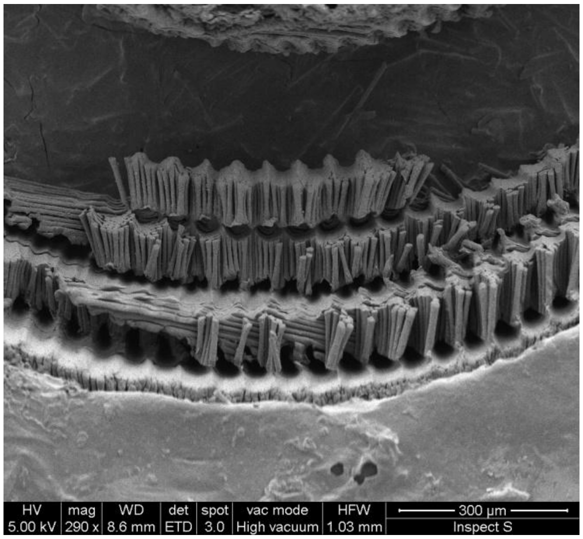

Figure 11 Image showing individual laser pulse witness marks and the short bundles of fibres.

An attempt to cut composites in a traditional manner, the way you would use a laser to cut metal leads to a great deal of surface damage and the exposure of the underlying fibres. Pervious work [10] shows this the typical damage one can expect with this approach. Figure 12 shows a tombstone shape cut from a CFRP composite MTM44-1. It can be seen that around the kerf the surface matrix and fibres have been damaged. The same laser system that cut the composite using the spiral drilling technique was used in this experiment.

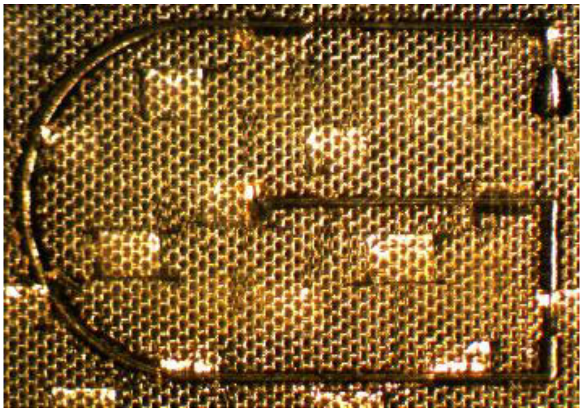

Figure 12 Traditional laser cutting of CFRP pre-preg.

Closer examination of the damage can be seen in figure 13. As said previously the authors believe that this damage is caused by the plasma plume. This belief is due in part to damage on the exit side of the CFRP sample in the traditional laser cutting trials. In the initial experiments in laser cutting of CFRP the sample holder held the sample too close to a back reflecting plate. This meant that laser energy was reflected onto the back surface which caused surface damage that was the carbon copy of the damage seen on the top surface of the sample but more extensive. Figure 14 shows a graph of the effect of cutting speed and CO_2 gas flow rates for CFRP pre-preg MTM44-1. It shows that by increasing either the cutting speed or by increasing the flow rate of the assist gas this surface damage can be reduced.

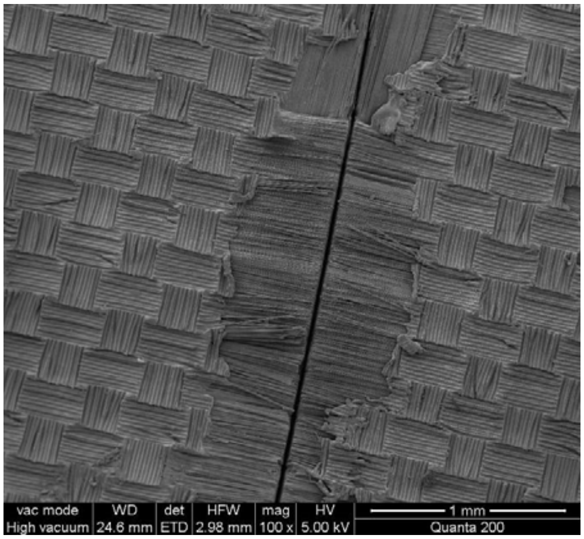

Figure 13 SEM image showing the central cut with associated surface damage.

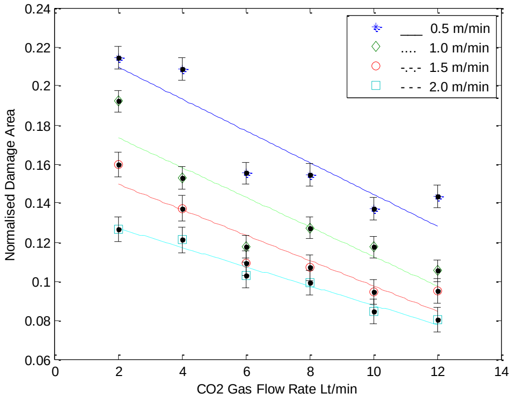

Figure 14 100W laser cutting of carbon composite MTM44-1 1ply CO_2 assist gas

Examination of figure 14 shows the general trend of increasing the flow rate of the assist gas, in this case carbon dioxide and increasing the feed rate of the laser cutting process. A quantitative figure can be placed on the improvement in surface quality. For the given feed rate of 0.5 m/min the improvement of increasing the flow rate of carbon dioxide from 2lt/min to 12lt/min we see an improvement of 60% reduction in damage with a reduction of just over 50% for 2.0 m/min. Increasing the cutting speed also gives similar reductions in damage. Increasing the cutting speed from 0.5 m/min to 2.0 m/min reduces the damage by nearly 70% at a flow rate 2lt/min and 60% at 12lt/min.

Laser processing CFRP with a fibre laser that delivers pulse energies that are in the micro Joule region is about "*Thermal Management*" of the process. Therefore to successful machine composite material we are looking to maximise the cutting speed to reduce the interaction time the CFRP. Also what thermal energy is deposited into the workpiece should be removed as efficiently as possible. This can be achieved using different pattern drilling strategies. Delivery of an assist gas to remove the heat is important and we are working on novel techniques to solve this problem for remote laser drilling using a scanning head that can be applied to a shop floor scenario.

Figure 15 shows a matrix of holes produced using laser spiral drilling. The sample is a carbon fibre pre-preg 2 ply with a peel ply layer. The time taken to drill a hole in the CFRP sample 750 μm thick was 5 second.

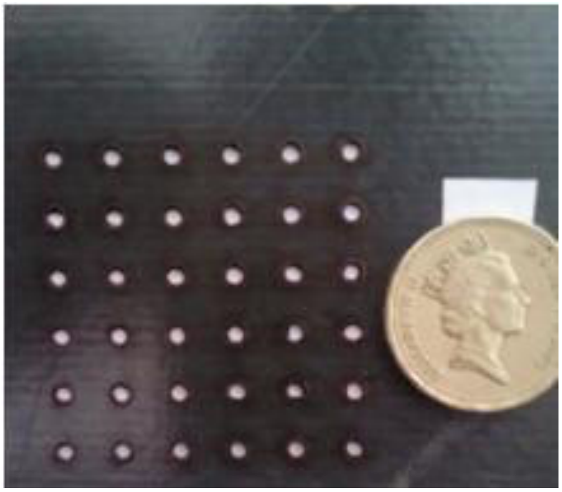

Figure 15 A matrix of 36 holes in a carbon fibre pre-preg.

Laser Milling

Though this paper is concerned with laser drilling of holes for acoustic liner applications another interesting laser material processing technique can be seen in figure 16. The fibre laser could have an important contribution to make in the aerospace sector with respect to laser milling. During this investigation and in previous experiments the authors have noted the quality of the finished surface perpendicular to the laser beam, the surface directly being machined. By altering the processing parameter it is possible to machine fine layers of composite material producing pockets in a composite structure that are required when machining out damage areas for repair. Figure 16 shows an image of composite material that has been machined in this way and shows the fine control the fibre laser can produce when operated as a laser milling tool.

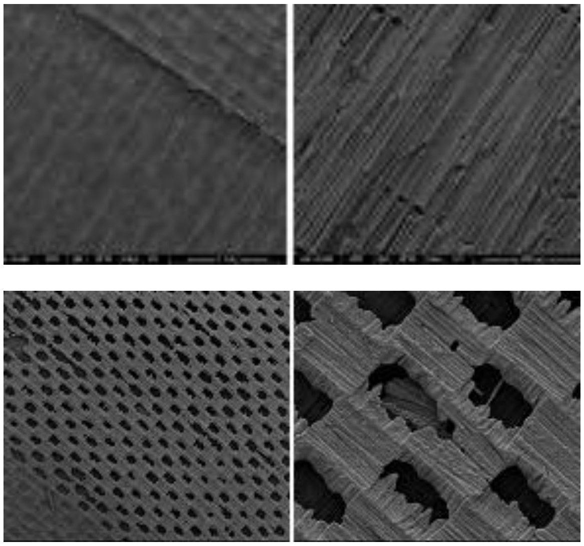

Figure 16 Laser milled surface of Pre-Preg CFRP

Summary

This investigation has shown that it is possible to use the new generation of fibre lasers in processing CFRP. A key application for fibre laser could be in laser drilling and this can be achieved using remote laser processing technology. Thermal management is the key to processing CFRP and the use of an assist gas such as CO_2 can reduce the thermal damage caused by the laser. Also reduction in the interaction time between the laser beam and the CFRP sample is an important feature of processing CFRP. This means that laser material processing of CFRP can take advantage of the high brightness of fibre lasers and the good beam quality that will allow processing with a small spot size, in the region of 10 μm.

Hole drilling strategies such as laser spiral drilling will play an important role in future laser material processing application for the aerospace and automotive sectors. The use of the fibre laser in machining CFRP will see applications in laser milling especially with respect to composite repair.

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