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APPLICATION REPORT

Report No: 139-3
Sample No: 2.2.1304

CONFIDENTIAL

REPORT: Carbon-fiber-reinforced-polymer cutting by Laser MicroJet®

for attention of Anonymous

by Ronan Martin, Synova SA

TASK

The Laser MicroJet® technology has been tested for cutting carbon-fiber-reinforced polymer. Several plates were provided for the trials, which were performed in your presence.

SAMPLE DESCRIPTION

Several plates were provided, but only three of them were processed: two in 5.2mm thickness and one in 2.6mm thickness.

Resin	epoxy
Fibers	continuous carbon fibers, 50 vol.%
Thickness	5.2mm and 2.6mm

PROCESS: INSTRUMENT & TEST PARAMETERS

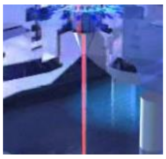
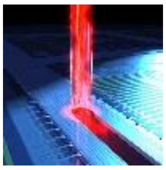
For these experiments, an LCS 300 equipped with a frequency-doubled Q-switched Nd:YAG laser with dual cavity has been used as the machine configuration in our lab. It is a manually loaded machine, allowing cutting and drilling any kind of metal piece.

Major advantages of the Laser MicroJet® technology with regards to your application are:

- Cutting of non-conductive materials
- Cutting of arbitrary shapes
- Low heat damage to the material
- Parallel cut walls

Release of application report			
Project Leader		Responsible Application Group	
Name:	Ronan Martin	Name:	Benjamin Carron
Date:	10.09.2013	Date:	11.09.2013
Visum:	ROM	Visum:	BC

In the table below, the typical processing parameters used in the experiments are summarized. More details concerning each sample are given in their respective sections.

	**SYSTEM**	Machine type	LCS 300	
	**MICROJET® PARAMETERS**	Nozzle diameter	100	*µm*
		MicroJet® diameter	83	*µm*
		Water pressure	200	*bar*
		Assist gas	He	
	**LASER PARAMETERS**	Laser type	L202G	
		Wavelength	532	*nm*
		Pulse frequency	10	*kHz*
		Delay between pulses	180	*ns*
		Internal power	175	*W*
		Power transmission in water jet	65	*%*
	**CUTTING PARAMETERS**	Working distance	12	*mm*
		Motion speed	50-200	*mm/s*
		Cutting speed	5.2mm thickness: 2 2.6mm thickness: 4	*mm/s* *mm/s*

The plates were fixed simply by clamping.

A thin protection plate was put below the coupling unit in order to prevent nozzle damage. Processing such a composite may indeed lead to particle projections and to some strong feedback that may damage the nozzle. This plate was drilled with the Laser MicroJet®, so that the water jet could go through it.

RESULTS - PRELIMINARY TESTS IN 5.2mm

At total of 33 holes were drilled in half of the plate for the preliminary tests, as seen in the picture below, where all holes are identified by a number. Although most of the holes are considered through, we should notice that nearly all the drilled cylinders had to be removed from the plate by pushing them. There were indeed generally some little bridges left.

PICTURE 1: Overall view of the processed sample.

The parameters used for all the holes are summarized in the table below. The biggest nozzle diameter of 100µm allowed to use more power and to cut more rapidly. We thus reached a cutting speed up to 0.5mm/s instead of the usual 0.25mm/s attained with the other nozzle diameters. It is however difficult to quantify the cutting speed precisely because of the smalls bridges that remain at the end of the cut.

We observed that the water pressure should not be too high in order to minimize jet instabilities during the process (because of minimized feedback).

We tried to make the radius vary slightly during the process on four of the holes by using a spiral path. It may have enhanced the process repeatability a bit, but it did not allow us to cut faster.

Sample	Nozzle diameter (µm)	Water pressure (bar)	Working distance (mm)	Frequency (kHz)	Power (W)	Motion speed (mm/s)	Passes	Cutting speed (mm/s)	Through	Comment
1		300				50	200		~	
2						10	40		~	
3		200	17			50	200		~	
4						10	40		yes	
5	**60**			14	50			0.25	~	
6			12						no	
7		100				50	200		no	not very repeatable due to pressure fluctuations
8			17						~	
9									~	
10			17			50	200		~	
11							40	0.25	yes	
12							40		yes	
13					110		42		yes	
14		300					42	0.24	yes	**radius variation**
15				10			42		yes	
16							45	0.22	yes	
17					55	10			~	
18	**80**		12						yes	
19		200							yes	
20					110		40		yes	
21				10				0.25	yes	
22									yes	
23		100							yes	
24				10+10	160	50	200		yes	
25						100	400		~	
26						100	400		yes	
27		100				50	200		~	
28				10+10			40	0.25	~	nozzle pb.
29		200	12				40		yes	
30	**100**				160	10	40		yes	
31		100		10			20	0.5	yes	
32		100					40	0.25	yes	
33		200					30	0.33	yes	

RESULTS – FINAL 5.2mm-THICK SAMPLE

In this sample, we mainly processed slices in a 40mm-wide band, as shown below. Two circles were also drilled, and cross-sections of these parts were made. All parts were identified by a number given by you during the visit. These numbers are written on the parts.

PICTURE 2: Overall view of the processed parts.

The parameters used for all the holes are summarized in the table below. The highest cutting speed was obtained with the maximum power.

Bridges appeared preferentially below the positions where sewing threads on the top surface were cut (pictures 3C and 3D). This may be due not to the thread itself, but rather to the higher thickness of pure epoxy resin at the top surface. While carbon is easy to cut, this resin seems to be hard to process with our technology. However, we noticed that smaller motion speeds could allow to minimize the size of bridges (picture 4).

We also noticed that a water pressure of 300bar (which is unusually high for such a big nozzle diameter) could lead to nozzle damage. This may be due to water accumulation between the nozzle and the diaphragm. (In that case, this issue would probably not happen with our other coupling unit design, where water can evacuate more easily).

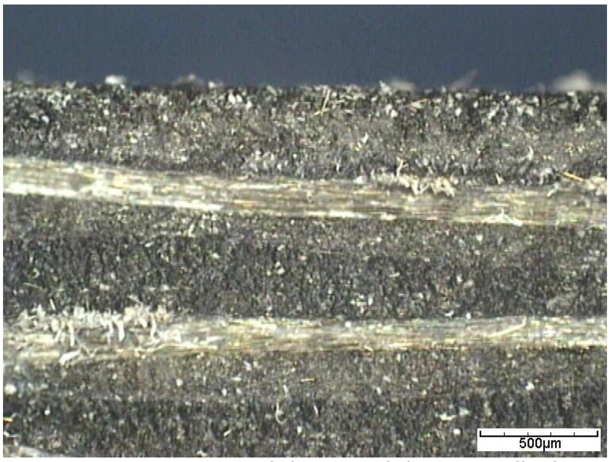
<table>
<tr><th>Part</th><th>Water pressure (bar)</th><th>Power (W)</th><th>Motion speed (mm/s)</th><th>Passes</th><th>Cutting speed (mm/s)</th><th>Through</th><th>Comment</th></tr>
<tr><td>1</td><td rowspan="10">200</td><td>175</td><td rowspan="4">100</td><td>100</td><td>1</td><td rowspan="2">yes</td><td></td></tr>
<tr><td>2</td><td>86</td><td>250</td><td>0.4</td><td></td></tr>
<tr><td>6</td><td>46</td><td>900</td><td>-</td><td>no</td><td></td></tr>
<tr><td>8</td><td rowspan="7">175</td><td>50</td><td rowspan="4">2</td><td rowspan="6">yes</td><td></td></tr>
<tr><td>9</td><td>200</td><td>100</td><td></td></tr>
<tr><td>10</td><td>400</td><td>200</td><td></td></tr>
<tr><td>11</td><td>50</td><td>25</td><td></td></tr>
<tr><td>12</td><td>400/100</td><td>200+50</td><td>0.25</td><td>smallest bridges</td></tr>
<tr><td>13</td><td rowspan="2">20</td><td rowspan="2">40/20</td><td rowspan="2">0.5/1</td><td>circle ø9.1mm, then lines</td></tr>
<tr><td>13bis</td><td>idem</td></tr>
<tr><td>14</td><td rowspan="2">300</td><td rowspan="2">175</td><td rowspan="2">100</td><td rowspan="2">100</td><td>1</td><td>yes</td><td rowspan="2">nozzle damage</td></tr>
<tr><td>14bis</td><td>-</td><td>no</td></tr>
<tr><td>15</td><td>100</td><td>175</td><td>100</td><td>100</td><td>1</td><td>yes</td><td></td></tr>
</table>

Please that the following parameters were constant and therefore do not feature in the table:

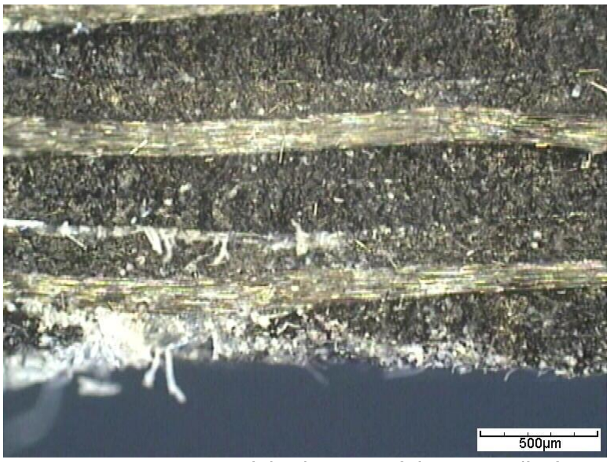
- **100µm nozzle diameter**
- **10kHz frequency**
- **12mm working distance**

The following pictures show the typical quality that was obtained in these experiments. While the cut wall is rather smooth on most of the surface (pictures 3A and 3B), there are often bridges below cut sewing threads (pictures 3C and 3D).

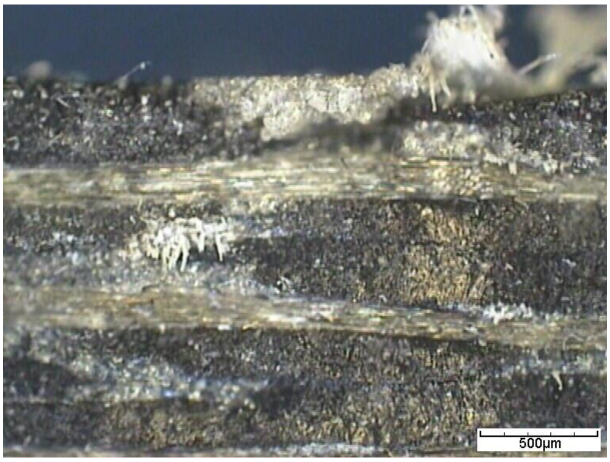
PART 11



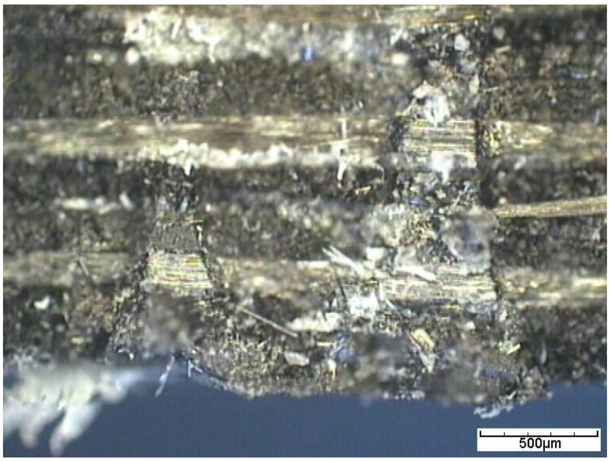
PICTURE 3A: Image of the top of the cut wall of part 11.



PICTURE 3B: Image of the bottom of the cut wall of part 11 (below 3A), showing no bridge.

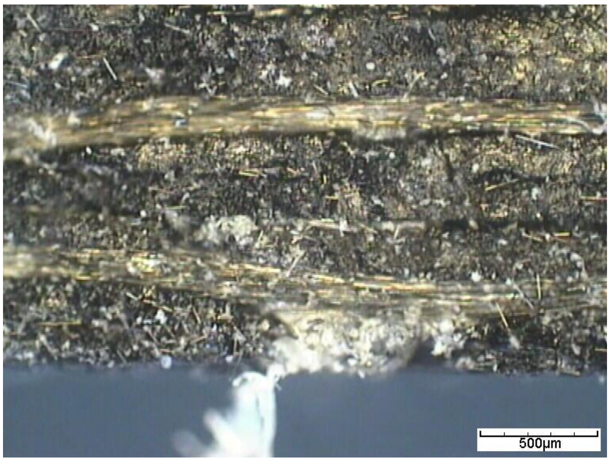


PICTURE 3C: Image of the top of the cut wall of part 11, where the sewing thread was cut.



PICTURE 3D: Image of the bottom of the cut wall of part 11, (below 3C), showing a bridge.

PART 12



PICTURE 4: Image of the bottom of the cut wall of part 12, below a cut sewing thread, showing a very small bridge.

RESULTS – 2.6mm-THICK SAMPLE

In this sample, we mainly processed again slices in a 40mm-wide band, as shown below. Two circles were again drilled, and cross-sections of these parts were made. As before, all parts were identified by a number given by you during the visit, and these numbers are written on the parts.

A difference, however, is that we grooved three lines on part 18, using different number of passes. We then made a cross-section of them in order to observe the profile.

PICTURE 5: Overall view of the processed parts.

<table>
<tr><th>Sample</th><th>Water pressure (bar)</th><th>Power (W)</th><th>Motion speed (mm/s)</th><th>Passes</th><th>Cutting speed (mm/s)</th><th>Through</th><th>Comment</th></tr>
<tr><td>16</td><td rowspan="7">200</td><td rowspan="7">175</td><td rowspan="3">100</td><td>50</td><td>2</td><td rowspan="7">Yes</td><td></td></tr>
<tr><td>17</td><td rowspan="2">25</td><td rowspan="4">4</td><td></td></tr>
<tr><td>18</td><td>cross section done for 5, 10 and 15 passes</td></tr>
<tr><td>19</td><td>200</td><td>50</td><td></td></tr>
<tr><td>20</td><td>400</td><td>100</td><td></td></tr>
<tr><td>21</td><td rowspan="2">50/100</td><td rowspan="2">20/25</td><td rowspan="2">2.5/4</td><td>circle ø9.1mm, then lines</td></tr>
<tr><td>21bis</td><td>idem</td></tr>
</table>

Again, the following parameters were constant and therefore do not feature in the table:

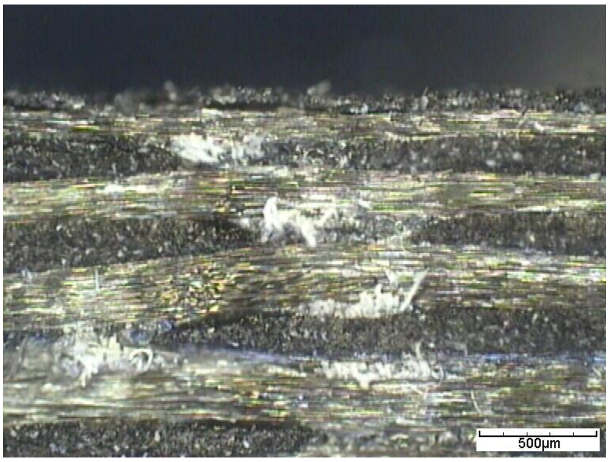
- **100µm nozzle diameter**
- **10kHz frequency**
- **12mm working distance**

Since the thickness is half as much as in the previous sample, the cutting speed is logically twice as much.

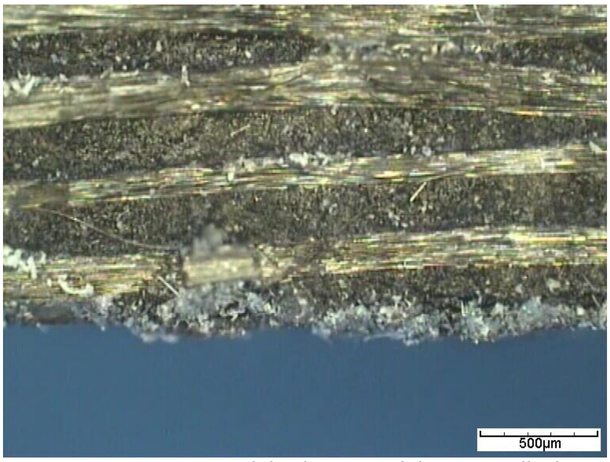
The following pictures show that quality is similar to the previous sample. There are still some bridges, but they are much smaller than previously (picture 5C).

Pictures 5D, 5E and 5F present the profiles of the grooved lines, respectively with 5, 10 and 15 passes. For reference, the cut begins to be partially through after 20 passes, and 25 passes were used in order to minimize bridges.

PART 18

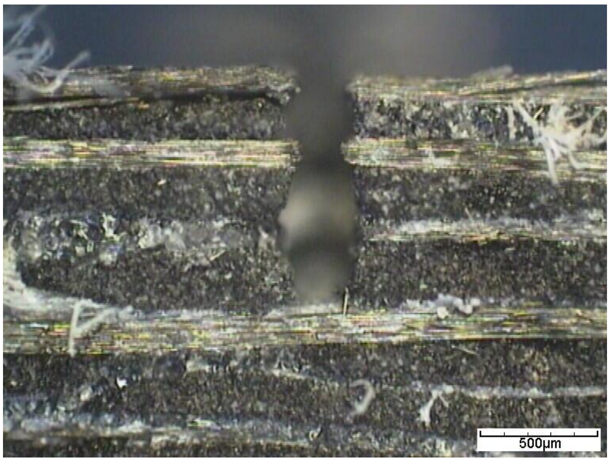


PICTURE 6A: Image of the top of the cut wall of part 18.

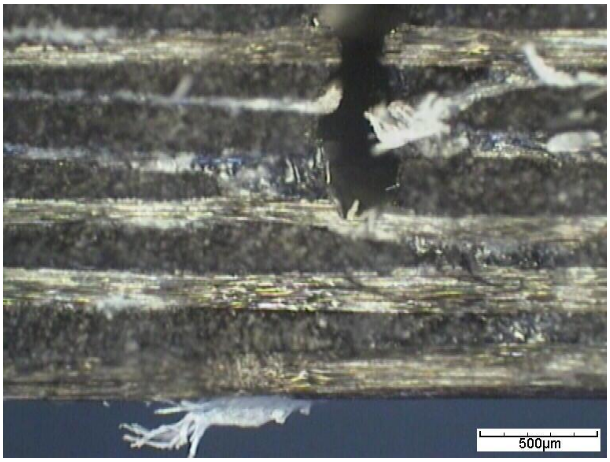


PICTURE 6B: Image of the bottom of the cut wall of part 18 (below 5A), showing no bridge.

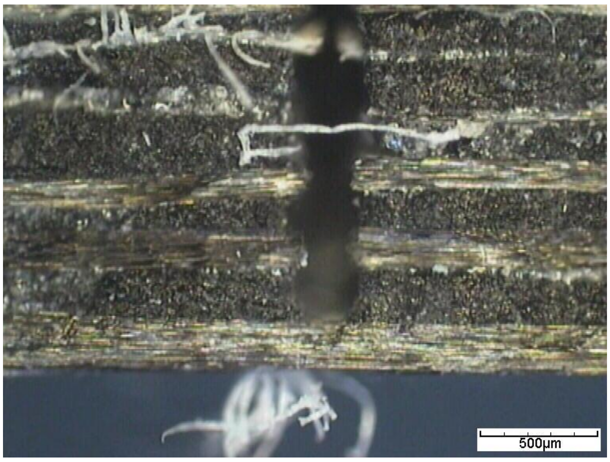
PICTURE 6C: Image of the top of the cut wall of part 18, showing a very small bridge.



PICTURE 6D: Cross-section of the line grooved with 5 passes.



PICTURE 6E: Cross-section of the line grooved with 10 passes.



PICTURE 6F: Cross-section of the line grooved with 15 passes, close to the bottom.

CONCLUSION

Priority	Goal	Achieved results
Cutting speed	300 mm/s	2-4 mm/s
Cut wall quality	equivalent to mechanical cutting	similar, although a bit rough
Cutting accuracy	± 50µm	about ± 10µm

The feasibility of cutting carbon-fiber-reinforced polymer was investigated in a series of tests in your presence. Several parts, mostly rectangular, were processed in order to evaluate the quality and cutting speed.

The quality is acceptable, but the process speed is much lower than the requirement of 300mm/s. We observed that the material is more difficult to cut where there is a thicker layer of resin at the surface (above sewing threads). Therefore, we think that the speed could be significantly improved on a composite containing a lower fraction of resin, a more regular resin distribution, or even with another resin. If you are willing, as discussed previously, to test different materials, we would be glad to do new tests.

We thank you for your interest in our technology. Our sales manager will contact you soon to receive your feedback and the analysis of these results and to discuss the further steps.