REPORT: Machining of nickel alloy and CMC by Laser MicroJet®

for attention of Anonymous

by Ronan Martin, Synova SA

TASK

The Laser MicroJet® technology has been tested on ceramic-matric composites and nickel superalloys. The aim was to assess the technology capabilities on several kinds of processes, involving cutting, engraving and drilling.

Since most of the parts were taken back by the customers when they left, the present report is focused on providing the parameters used for each tests instead of providing analysis. The used NC programs will be sent separately by email.

SAMPLE DESCRIPTION AND PREPARATION

CMC PLATES	Material	Ceramic-matric composite (SiC/SiC)
	Thickness	0.070 in / 0.100 in / 0.125in / 0.165in
SUPERALLOY PLATES	Material	Nickel-based superalloy (grade N5)
	Thickness	0.070 in
STAIR-SHAPED COUPONS	Material	Nickel-based superalloys (four grades)
	Thickness	0.15in / 0.20in / 0.25in / 0.30in

The objectives were to:

- trepan holes, cut bars and engrave slots in CMC panels,
- process shaped holes in CMC and nickel-alloy plates
- drill small holes in stair-shaped nickel-alloy coupons

We also performed a few ablation tests in CMC and in nickel alloy.

Release of application report			
Project Leader		Responsible Application Group	
Name:	Ronan Martin	Name:	Benjamin Carron
Date:	01.09.2014	Date:	01.09.2014
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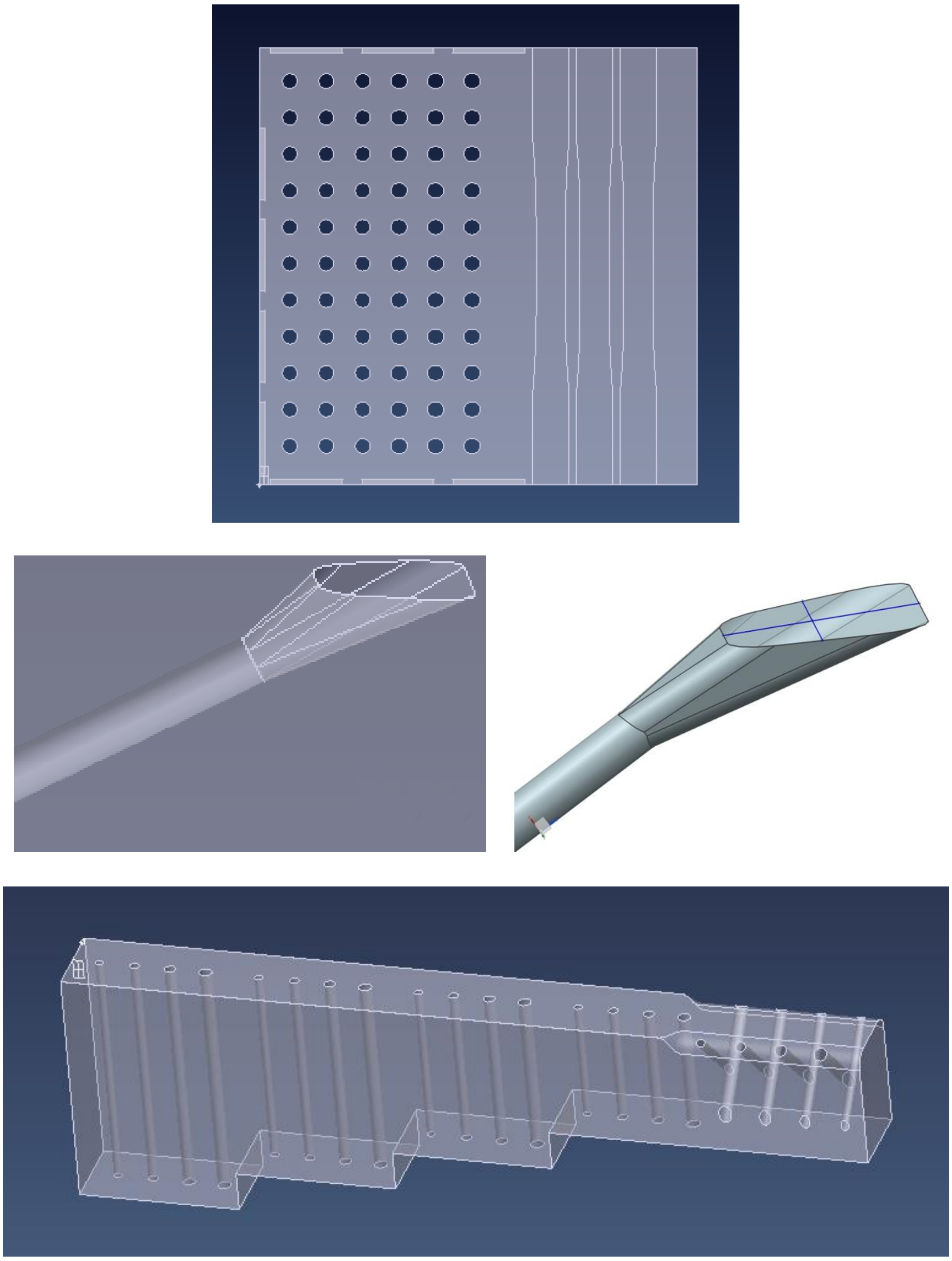


FIGURE A: Illustration of the parts that had to be processed
Top: CMC plate with holes to drill, bars to cuts and slots to engrave
Middle: Shaped holes, with the hole being adjacent to either the shorter or the longer edge of the trapezoid
Bottom: Stair-shaped coupon, where small holes have to be drilled at 90° and 45°.

PROCESS: INSTRUMENT & TEST PARAMETERS

For these experiments, two different machines were used, because different nozzle diameters were needed. We therefore used machines with different laser fiber diameters, which allowed:

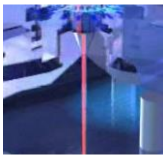
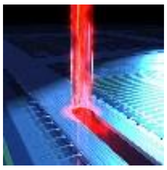
- on one side using small nozzles thanks to a small laser spot;
- on the other side using larger nozzles with more power.

These machine were equipped with frequency-doubled Q-switched Nd:YAG lasers.

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

- Cutting of non-conductive materials
- Advantageous process rates
- Cutting of arbitrary shapes
- Low heat damage to the material

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

	**SYSTEM**	Machine type Optical head type	LCS 300 Compact	LCS 150 Standard
	**MICROJET PARAMETERS**	Nozzle diameter	70 *µm*	30 *µm*
		MicroJet diameter	58 *µm*	25 *µm*
		Water pressure	300 *bar*	400 *bar*
		Working distance	10 *mm*	8 *mm*
		Helium flow	0.9 *L/min*	1.1 *L/min*
	**LASER PARAMETERS**	Laser type	L202G	L51G
		Fiber diameter	200 *µm*	100 *µm*
		Wavelength	532 *nm*	532 *nm*
		Frequency	14 *kHz*	10 *kHz*
		Pulse width	~200 *ns*	170 *ns*
		Inter-pulse delay	300 *ns*	n.a.
		Internal power	110 *W*	33 *W*
		Power in the jet	84 *W*	12.5 *W*
	**CUTTING PARAMETERS**	Motion speed	Cut: 50 *mm/s* Diffuser: 30 *mm/s* Drill: 2 *mm/s*	Drill: 1 *mm/s* Finish: 2 *mm/s*
		Step for engraving and drilling	35 *µm*	Drill: 15 *µm* Finish: 5 *µm*

A diaphragm (small metal plate put below the nozzle) was used in order to protect the nozzle from particle contamination and from water-jet instabilities due to feedback. This is a standard procedure in this type of application.

The samples were hold:

- horizontal for the cutting tests and ablation tests,
- with an angle of 25° compared to the jet for the shaped holes.

The **cutting and trepanning** was performed using a multipass strategy.

The **ablation** tests were done by hatching: scanning alternatively a layer of horizontal lines, then a layer of vertical lines, and repeating this pattern a certain number of times.

The **diffuser shapes** were processed before hole drilling. We wrote NC programs that simulate the slicing of a diffuser shape into several layers. Because there is no focal point in our technology, the slicing can be done parallel to the surface of the material. There are two versions of the NC program: one with the hole adjacent to the small edge, and one with the hole of the longer edge, as seen in Figures A and B below. Each layer has the shape of a rounded trapeze. The layers become successively smaller (while the corner radius is kept constant) as seen in Figures B and C. The amount by which each layer decreases is inversely proportional to the number of layers. Each layer is engraved by offset filling, as shown in Figure D, with a step of half the nozzle diameter.

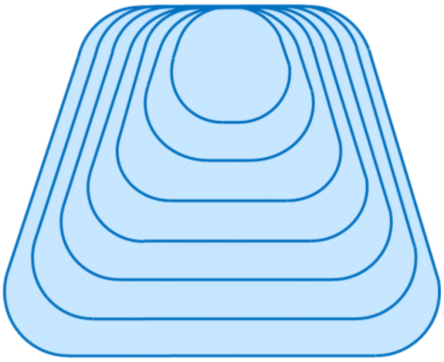


FIGURE B: Variation of the size of successive layers (diffuser with hole on the smaller edge)

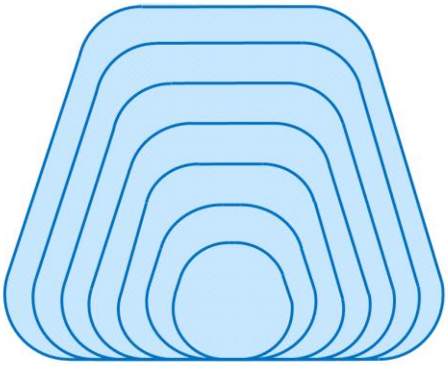


FIGURE C: Offset filling in one layer (diffuser with hole on the longer edge)

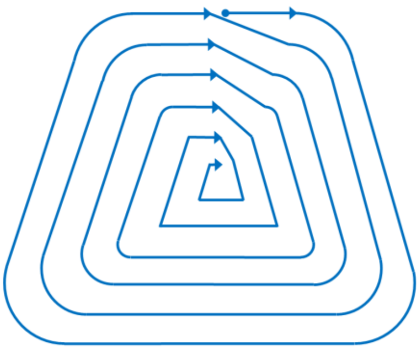


FIGURE D: Offset filling in one layer

The **small holes** were drilled using a double-spiral path, as illustrated in Figure E, where the path first follows the blue arrows (inwards) and then red arrows (outwards), and is repeated as many times as necessary. The 30µm or 25µm step value given in the table above corresponds to the distance indicated by the black double arrow. It corresponds to half of the nozzle diameter.

A spiral path is necessary to drill deep holes with a high aspect ratio. In this case, the hole begins to be cut through in the center, and gets progressively wider on the backside, minimizing the taper.

In order not to lose time on the final passes which ensure that the taper is minimized, a modified spiral path can be used, where the central part is omitted (Figure F).

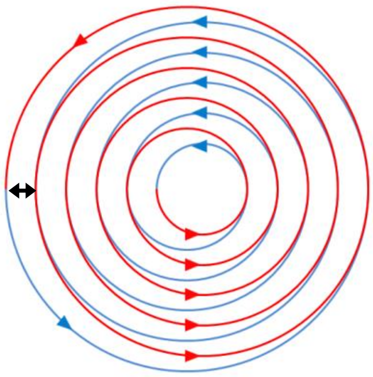


FIGURE E: Illustration of the path used for spiral drilling, following first the blue arrows, then the red ones..

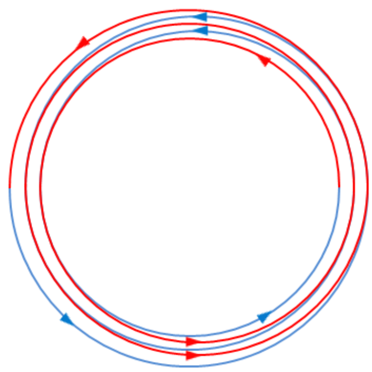


FIGURE F: Illustration of the path used for finishing, where the central part is omitted, and the spiral step is smaller.

The **slots** were generally processed by hatching: scanning layers of horizontal lines and repeating the pattern. No vertical lines were done in this case because of the small slot width. We used several variations:

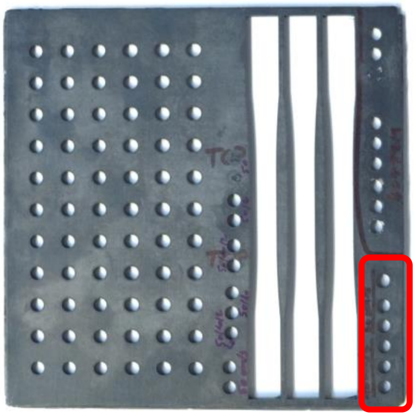
- In the first tests, we scanned the line layer always upwards.
- Then we scanned alternatively upwards and downwards (what is further called “bi-hatching” for sake of conciseness).
- In the last tests, we also engraved a rectangular outline before engraving the slots.
- Also, one slot was processed using a rectangular spiral, similar to the double-spiral path illustrated in Figure E.

RESULTS

1 Hole trepanning and bar cutting in CMC

Note: The pictures always show the top side as it was used for the process.

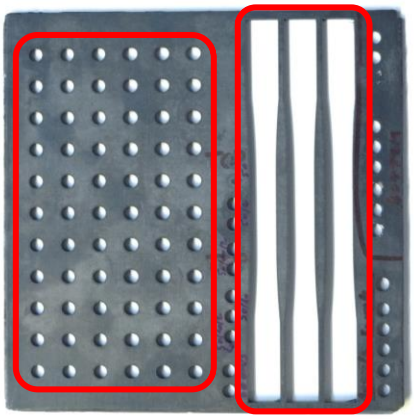
The preliminary tests were carried out on three different panel thicknesses, ending with the final panel. The first trial, performed on an LCS150 machine and a 30µm nozzle gave the best roughness: Ra=0.9µm in general and Ra=0.2µm in the matrix. The next trials, performed on an LCS300 machine and a 70µm nozzle, aimed to get a satisfactory roughness with an improved process time. The last tests were performed on the final plate (as outlined on the right).



Cut number	Cut type	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Passes	Time
#1	line	0.165 in	13 W	10 kHz	400 bar	10 mm/s	85	13’21
#2	line	0.165 in	84 W	14 kHz	220 bar	10 mm/s	27	4’09
#3	line	0.165 in	84 W	14 kHz	220 bar	50 mm/s	124	3’57
#4	line	0.165 in	84 W	14 kHz	300 bar	10 mm/s	22	3’29
#4B	line	0.165 in	84 W	14 kHz	300 bar	10 mm/s	24	3’41
#5	line	0.165 in	46 W	10 kHz	300 bar	10 mm/s	67	10’30
#5B	line	0.165 in	46 W	10 kHz	300 bar	10 mm/s	69	10’49
#5C	line	0.100 in	46 W	10 kHz	300 bar	10 mm/s	47	4’15
#5D	line	0.100 in	46 W	10 kHz	300 bar	10 mm/s	49	4’26
#6	line	0.100 in	84 W	14 kHz	300 bar	10 mm/s	17	1’31
#6B	line	0.100 in	84 W	14 kHz	300 bar	10 mm/s	19	1’34
#7	line	0.100 in	84 W	14 kHz	300 bar	50 mm/s	71	1’15
#F1	circle	0.125 in	84 W	14 kHz	300 bar	10 mm/s	25*	45 s
#F2	circle	0.125 in	84 W	14 kHz	300 bar	10 mm/s	25*	45 s
#F3	circle	0.125 in	84 W	14 kHz	300 bar	10 mm/s	25*	45 s
#F4	circle	0.125 in	84 W	14 kHz	300 bar	50 mm/s	125**	45 s
#F5	circle	0.125 in	84 W	14 kHz	300 bar	50 mm/s	125**	45 s
#F6	oval	0.125 in	84 W	14 kHz	300 bar	50 mm/s	125**	48 s

* through after 19-21 passes
** through after 81-83 passes

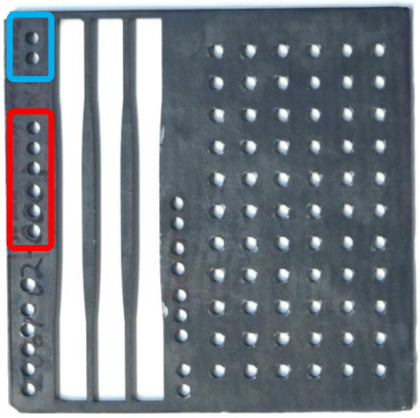
Then final cuts were then performed: 30 circles, 30 ovals and three bars, as seen on the right. The bars were cut in two steps: first the long, curved lines, and then the short segments at both extremities. The bars did not fall by themselves, and had to be pushed down. We thought that it was due to bridges left in the corners. However, it appeared that there were some bridges along the long lines. A few more passes would have been needed in that case.



We observed the presence of chipping on the backside of the panel. This chipping occurred at four specific positions in each hole, at 90° of each hole that was drilled at 50mm/s. However, the three preliminary holes drilled at 10mm/s showed a much nicer backside. These chipping were not present on the lines, certainly because of their orientation.

Cut	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Passes	Time (total)
30 circles	0.125 in	84 W	14 kHz	300 bar	50 mm/s	100	18’33
30 ovals	0.125 in	84 W	14 kHz	300 bar	50 mm/s	90	17’43
3 bars	0.125 in	84 W	14 kHz	300 bar	50 mm/s	90	28’33

To confirm that the chipping was not due to a defect on the backside, we turned the panel over and drilled three holes at 50 mm/s, and three others at 10mm/s, as outlined in red on the right. We observed the same behavior as before, which confirmed the influence of motion speed on chipping.

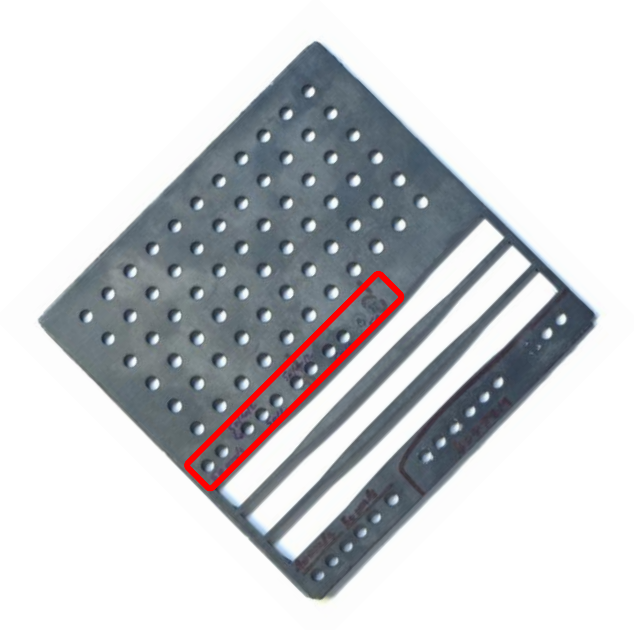


Then, in order to get a good roughness and minimize chipping, we drilled two holes using two speeds: most of the hole was drilled at 50mm/s, and the last passes were done at 10mm/s. The holes are outlined in blue on the right.

Cut series	Cut type	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Passes	Time (per circle)
1	circle (3x)	0.125 in	84 W	14 kHz	300 bar	50 mm/s	100	39 s
2	circle (3x)	0.125 in	84 W	14 kHz	300 bar	10 mm/s	20	39 s
3	circle (2x)	0.125 in	84 W	14 kHz	300 bar	1) 50 mm/s 2) 10 mm/s	1) 76 2) 4	38 s

Then, in order to perfectly confirm that the chipping was due to the fiber orientation and not the machine's axes, we drilled more holes after having turned the panel at 45°. The chipping positions did not change, confirming our hypothesis.

We then drilled several series of holes using different combinations of motion speeds. The last hole was not drilled through on purpose, for the sake of analysis.



Cut series	Cut type	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Passes	Time (per circle)
1	circle (2x)	0.125 in	84 W	14 kHz	300 bar	50 mm/s	100	39 s
2	circle	0.125 in	84 W	14 kHz	300 bar	1) 50 mm/s 2) 10 mm/s 3) 2 mm/s	1) 76 2) 4 3) 10	127 s
3	circle (2x)	0.125 in	84 W	14 kHz	300 bar	1) 50 mm/s 2) 10 mm/s	1) 76 2) 10	48 s
4	circle (2x)	0.125 in	84 W	14 kHz	300 bar	1) 50 mm/s 2) 10 mm/s 3) 2 mm/s	1) 76 2) 4 3) 3	66 s
5	circle (2x)	0.125 in	84 W	14 kHz	300 bar	1) 50 mm/s 2) 2 mm/s	1) 76 2) 4	66 s
6	circle (2x)	0.125 in	84 W	14 kHz	300 bar	50 mm/s	76	31 S

2 Slot engraving in CMC

The slots were processed on a different panel, which was 0.100in thick. We made nine slots and then cut them in the middle for the sake of analysis, as seen below. In slots 7 and 9, a rectangular outline was engraved prior to the slot engraving. The difference between the two slots is the offset of this outline: 35µm on each side for slot 7, and 70µm for slot 9. From the microscope observation, slot 9 had the best defined shape.

Slot number	Cut type	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Passes	Time
1	Hatching	0.100 in	84 W	14 kHz	300 bar	50 mm/s	40	2’49
2	Rectangular spiral	0.100 in	84 W	14 kHz	300 bar	50 mm/s	40	3’53
3	Hatching	0.100 in	84 W	14 kHz	300 bar	50 mm/s	27	1’55
4	Bi-hatching (upwards then downwards)	0.100 in	84 W	14 kHz	300 bar	50 mm/s	22	1’30
5	Bi-hatching	0.100 in	84 W	14 kHz	300 bar	30 mm/s	20	1’36
6	Bi-hatching	0.100 in	84 W	14 kHz	300 bar	30 mm/s	13	1’18
7	1) Rectangle 2) Bi-hatching	0.100 in	84 W	14 kHz	300 bar	50 mm/s	1) 80 2) 22	2’28
8	Rectangle (outline only)	0.100 in	84 W	14 kHz	300 bar	50 mm/s	80	1’02
9	1) Rectangle 2) Bi-hatching	0.100 in	84 W	14 kHz	300 bar	50 mm/s	1) 80 2) 22	2’30

Two additional slots were machined on the side of the 0.070in- thick part described in the next section (Figure 2C, not showed on the picture). These slots are identical to the slots 8 and 9 described in the table above.

3 Shaped holes and ablation tests in CMC and nickel alloy

3.1 Results in CMC

Two pieces of 0.100in and 0.070in panels, were used to process shaped holes and to perform ablation tests, as presented below. Shaped holes followed the two different designs described previously (Figures A, B and C). One diffuser shape was processed without further hole drilling for the sake of analysis.

Since initial tests showed that the holes drilled adjacent to the longer edge left a mark, the hole was offset from this edge by 200µm.

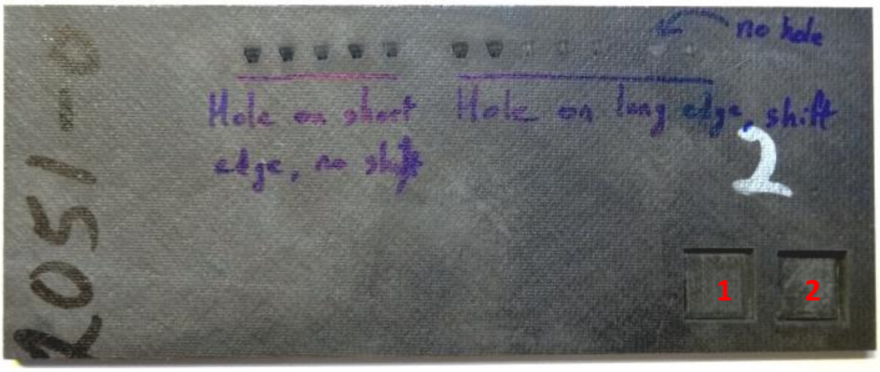


FIGURE 2B: 0.100in panel

FIGURE 2C: 0.070in panel

Process	Panel thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Layers	Time	Depth
Ablation test 1	0.100 in	84 W	14 kHz	300 bar	50 mm/s	6	13’21	1.03 mm
Ablation test 2	0.100 in	84 W	14 kHz	300 bar	50 mm/s	10	22’15	1.76 mm
Ablation test 3	0.070 in	23 W	14 kHz	300 bar	30 mm/s	4	7’46	0.42mm
Diffuser engraving	Both	23 W	14 kHz	300 bar	30 mm/s	80	62 s	n.a.
Hole drilling	0.100 in	84 W	14 kHz	300 bar	2 mm/s	16	119 s	n.a.
Hole drilling	0.070 in	84 W	14 kHz	300 bar	2 mm/s	10	75 s	n.a.

3.2 Results in nickel alloy

Similar tests were performed in nickel-alloy samples. Again, one diffuser shape is processed differently than the others, but this time a hole was not only drilled, but a finishing process was used to enhance the quality on the back side. This cleaning process involved the same full spiral path, just done at a lower speed.

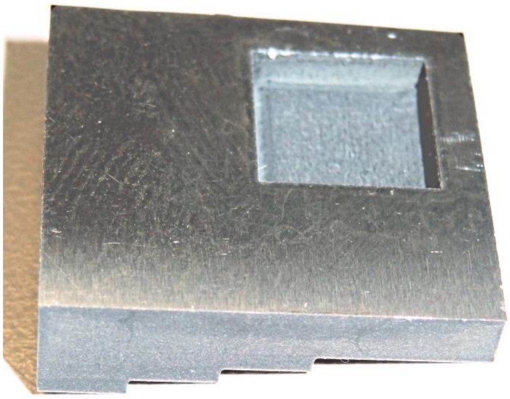


FIGURE 3C: Stair-shaped coupon

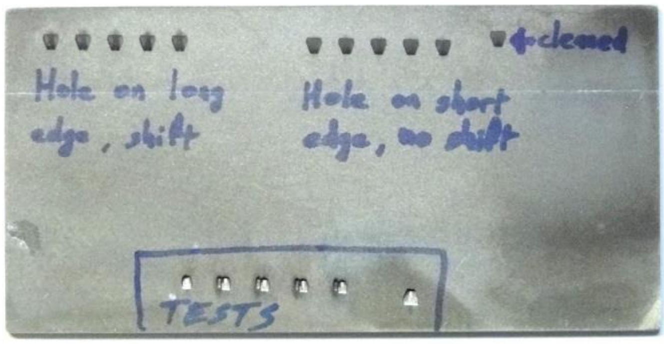


FIGURE 3D: 0.070in-thick part

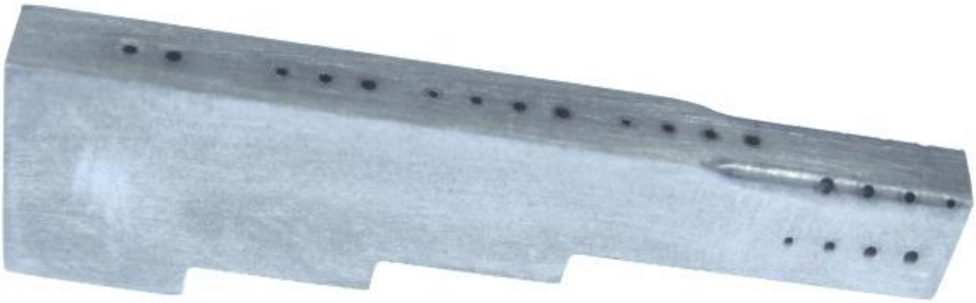
Process type	Coupon	Power in jet	Rep. rate	Water pressure	Motion speed	Layers	Time	Depth
Ablation test	stair	84 W	14 kHz	300 bar	50 mm/s	6	13'21	1.03 mm
Diffuser engraving	0.070''	23 W	14 kHz	300 bar	30 mm/s	80	62 s	n.a.
Hole drilling	0.070''	84 W	14 kHz	300 bar	3 mm/s	6	33 s	n.a.
Hole cleaning	0.070''	84 W	14 kHz	300 bar	1) 2mm/s 2) 1mm/s	1) 6 2) 6	1) 30 s 2) 60 s	n.a

4 Drilling of small holes in nickel alloy

Small holes (diameters 10mil, 12mil, 14mil and 16mil) were drilled in stair-shaped coupons in four different grades. Most of the holes were drilled at 90°, but some were drilled at 45°. As discussed during your visit, some holes were omitted in the two highest thicknesses:

- 10mil and 12mil diameters in the 0.30in thickness
- 10mil in the 0.25in thickness

The reason for these omissions was that the 10mil hole could not be achieved in the 0.30in thickness, while the others were at the limit of the process in this setup (aspect ratio 1:25), and took about 10min to drill.



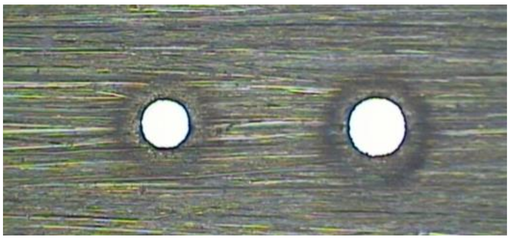
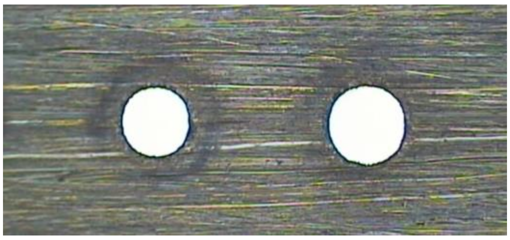
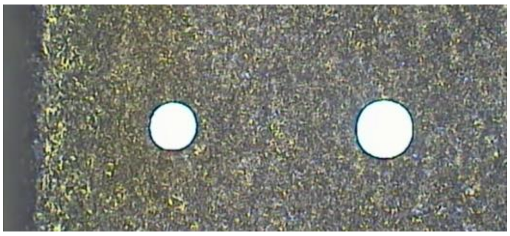
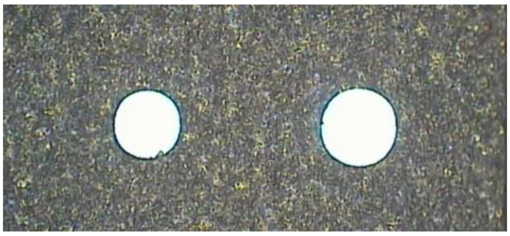
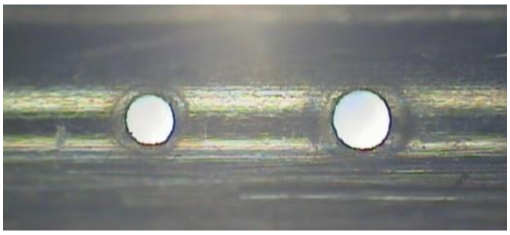
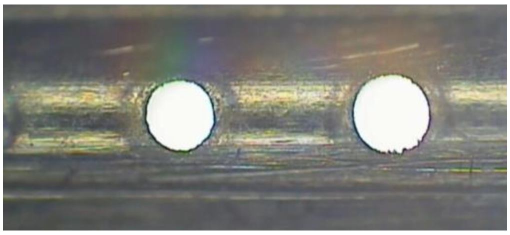
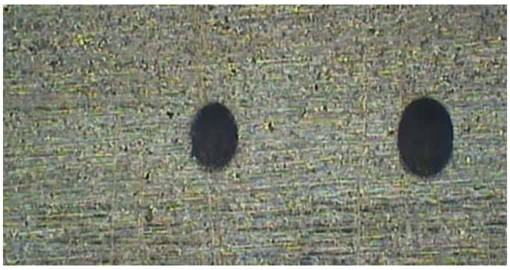
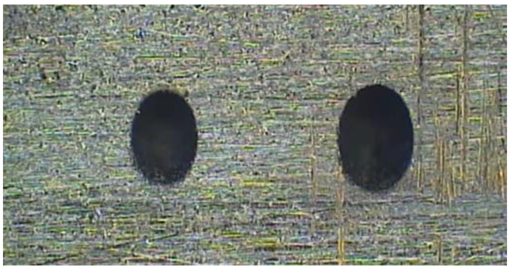
The table below present the parameters used for the different holes. We realized that the accumulation of water over the diaphragm was affecting negatively the process, so we regularly blew some air to remove the water, especially if one hole took longer than expected. This was done manually in our case because of the used machine configuration, but it can be automatized.

Hole diameter	Angle	Thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Layers	Time
14mil	90°	0.030 in	12.5 W	10 kHz	400 bar	1 mm/s	30	5’42
16mil	90°	0.030 in	12.5 W	10 kHz	400 bar	1 mm/s	20	4’50
12mil	90°	0.025 in	12.5 W	10 kHz	400 bar	1 mm/s	30	4’01
14mil	90°	0.025 in	12.5 W	10 kHz	400 bar	1 mm/s	20	3’48
16mil	90°	0.025 in	12.5 W	10 kHz	400 bar	1 mm/s	15	3’37
10mil	90°	0.020 in	12.5 W	10 kHz	400 bar	1 mm/s	100	8’10
12mil	90°	0.020 in	12.5 W	10 kHz	400 bar	1 mm/s	20	2’41
14mil	90°	0.020 in	12.5 W	10 kHz	400 bar	1 mm/s	15	2’51
16mil	90°	0.020 in	12.5 W	10 kHz	400 bar	1 mm/s	10	2’25
10mil	90°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	30	2’27
12mil	90°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	10	1’20
14mil	90°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	8	1’31
16mil	90°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	6	1’27
10mil	45°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	20	1’38
12mil	45°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	8	1’04
14mil	45°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	6	1’08
16mil	45°	0.015 in	12.5 W	10 kHz	400 bar	1 mm/s	5	1’12

We also used a finishing process after the drilling. In this case, we used a partial spiral path, as illustrated in Figure F. The minimum diameter was set as equal to the maximum diameter minus 20µm, and the spiral step was decreased from 15µm to 5µm.

Hole diameter	Angle	Thickness	Power in jet	Rep. rate	Water pressure	Motion speed	Repetitions	Time
14mil	90°	0.030 in	12.5 W	10 kHz	400 bar	0.5 mm/s	10	4
12mil	90°	0.025 in	12.5 W	10 kHz	400 bar	0.5 mm/s	10	4’01
10mil	90°	0.020 in	12.5 W	10 kHz	400 bar	0.5 mm/s	10	8’10
10mil	90°	0.015 in	12.5 W	10 kHz	400 bar	0.5 mm/s	5	2’27
10mil	45°	0.015 in	12.5 W	10 kHz	400 bar	0.5 mm/s	10	1’38

The microscope pictures below show the good quality that was obtained. The hole shape is well defined, and heat damage is limited, especially on the back side. We observed that the front side of a few holes may have been affected by air blowing when it was done during lasing, but this can easily be avoided by switching the laser shutter off when blowing air.

<table>
<tr><th></th><th>10mil</th><th>12mil</th><th>14mil</th><th>16mil</th></tr>
<tr><td>FRONT SIDE DRILLED AT 90°</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>BACK SIDE DRILLED AT 90°</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>FRONT SIDE DRILLED AT 45°</td><td colspan="2"></td><td colspan="2"></td></tr>
<tr><td>BACK SIDE DRILLED AT 45°</td><td colspan="2"></td><td colspan="2"></td></tr>
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CONCLUSION

The cutting, engraving and drilling of CMC and nickel alloy was investigated on a Synova LCS300 and an LCS150. These machines are based on the Laser MicroJet® technology and combine the advantages of a high-energy pulsed laser with a hair-thin water jet. While the laser is used for material ablation, the water jet is used for guiding the laser light, cooling the edges and preventing the sample from particle contamination.

In these tests, we showed that we can:

- reach an average roughness below 1µm in 0.165in-thick CMC, , with a cutting speed of 7mm/min , using a small nozzle,
- reach a cutting speed of 30mm/min in 0.165in-thick CMC while keeping an average roughness within specifications, using a bigger nozzle
- process slots using hatching
- process shaped holes in coated and uncoated nickel alloy or CMC, using a single setup
- reach an hole aspect ratio up to 1:25 in nickel alloy.

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