AS FAST AS LASER, AS PRECISE AS EDM

Laser MicroJet® (LMJ) is a hybrid technology that guides a laser beam within a hair-thin water jet enabling a long working length. While it remains a thermal technology, the coupling with the water jet enables better local cooling and cleaning. Swiss company Synova is the pioneer in exploring and commercialising this cool technology. In the Netherlands, Ter Hoek is a service provider exploiting this technology, next to its main expertise in EDM technology, for the high-tech manufacturing industry across Europe and beyond.

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AUTHORS' NOTE

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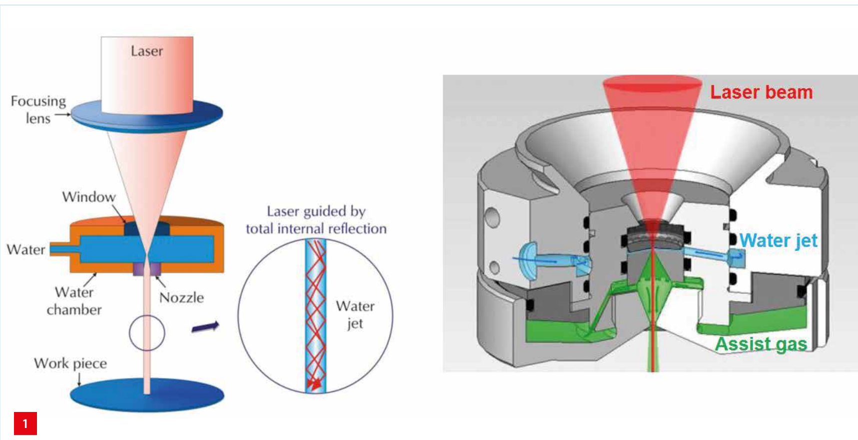
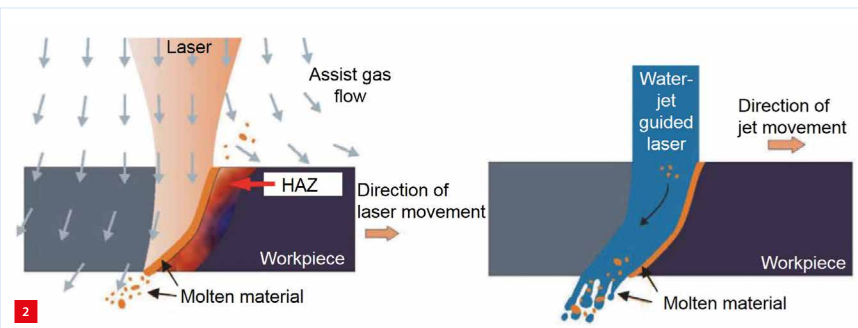
Introduction

In the manufacturing industry, laser technology has been applied in various processes including welding, cutting, drilling, grooving, surface treatment, and ablation deposition. Laser cutting is among them the most widely applied. Compared with mechanical cutting, laser cutting is a contact-free process, which can make smaller and cleaner cuts, with less material contamination, physical damage, and waste. As there is in principle no tool wear, laser cutting is highly reproducible and requires less intervention.



LMJ principle (left) and the coupling of laser and water jet (right). (Image credit: Synova)



Comparison of the heat-affected zones (HAZ) for conventional dry laser and water-jet guided laser (LMJ) processing, respectively [1].

The Laser MicroJet (see the videos [V1, V2]) is a hybrid technology, which combines a laser with a transparent water jet that precisely guides the laser beam by means of total internal reflection at the water/air interface (Figure 1, left), in a manner similar to conventional optical fibres. The coupling unit (Figure 1, right) is a complex precision device designed to produce a very stable, non-turbulent water jet, surrounded by assist gas (helium) to further improve the stability of the long water jet. In general, the jet working length is approximately 1,000 times the diameter of the nozzle, which means a working length of around 50 mm for a 50-μm-diameter nozzle.

The low-pressure (up to 800 bar) water jet continually cools the cutting zone and efficiently removes the debris. LMJ technology resolves the significant problems associated with dry lasers, such as heat-affected zones (HAZ, Figure 2), contamination, deposition, oxidation (Figure 3), micro-cracks, deformation, hence a lack of accuracy in particular for thicker materials.

Figure 3 illustrates the difference in cutting quality between conventional dry laser and LMJ processing on a stainless-steel plate. As can be clearly seen, there is almost no HAZ with LMJ and the cutting edge is sharp and free of burrs.

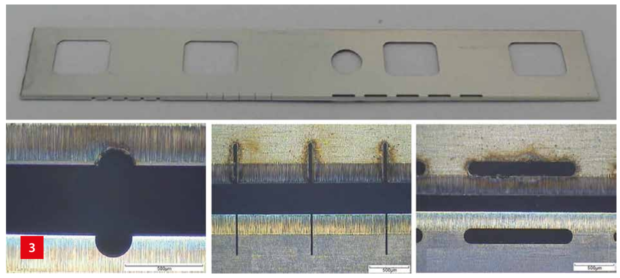
From the graph of the absorption coefficient in water (Figure 4), it can be seen that a large range of laser types (from ultraviolet to infrared) has an absorption coefficient below 0.2 cm^{-1}, which is regarded as the threshold of tolerable absorption, or the transparency 'window' as indicated. Among them, the green laser (532 nm) is very close to the optimum as it has the lowest absorption coefficient.

A recent LMJ application is the drilling of holes in aerospace turbine metal blades provided with a ceramic

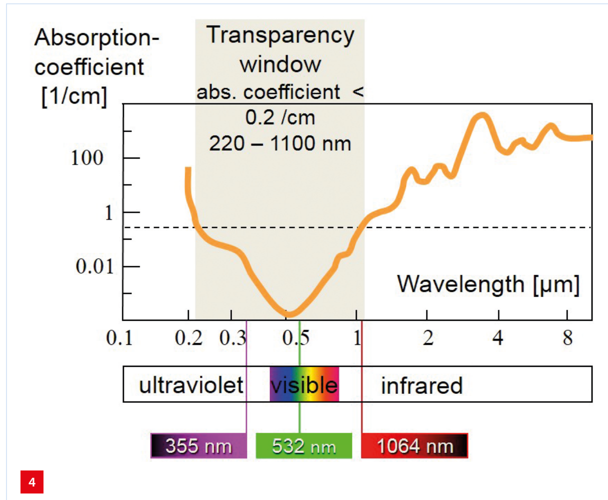
Table 1
Comparison of LMJ with other precision-cutting technologies (data dependent on various factors and therefore only indicative) [2, 3].

	LMJ	Laser*	Wire-EDM	(Abrasive) water jet	Milling/ cutting
Materials	Non-reflective materials		Conductive materials	Not ideal for brittle or extreme hard materials	
Thickness (up to)	20 mm	A few mm	50 cm	A few cm	
Cutting speed (up to)	A few mm/s	A few cm/s for thin materials	A few mm/ min	A few mm/s	
Part accuracy (±, down to)	A few µm	25 µm	A few µm	25 µm	A few µm
R_a (down to)	0.1 µm	0.3 µm	0.05 µm	1 µm	0.3 µm
Kerf width (down to)	0.03 mm	0.08 mm (V-shape)	0.03 mm	0.5 mm	1 mm
Edge quality	Excellent	Thickness-dependent	Excellent	Good	Good
Heat-affected zone	Almost none	Yes	Some	None	None
Set-up	Fast	Fast	Slow (start holes needed)	Fast	Moderate

** Excluding ultra-short-pulse laser.*



Below a stainless-steel shaver blade, three comparisons of cutting quality between conventional laser (middle row) and LMJ (bottom row) processing. (Image credit: Synova)



Water absorption spectrum from UV to IR wavelength. (Image credit: Synova)

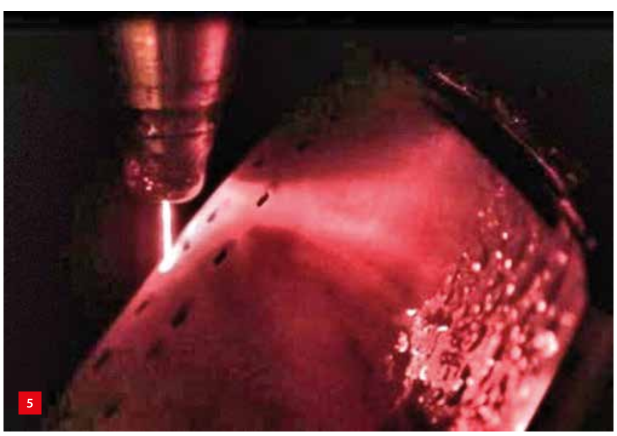
thermal barrier coating. The removal of the ceramic coating and the through-drilling of the metal blade are executed in one set-up (Figure 5), which is not possible with a traditional laser due to its short working length.

Table 1 gives a comparison of LMJ with other precision-cutting technologies. As can be seen, LMJ features easy set-up, high precision, small kerf and good edge quality. Compared with conventional dry laser processing, it can process thicker material with much less HAZ. Wire-EDM (electrical discharge machining) on the other hand, shows characteristics similar to that of LMJ but has a slower set-up and a lower process speed. However, depending on the product geometry and product quantity, wire-EDM could be more economical, as will be discussed later.

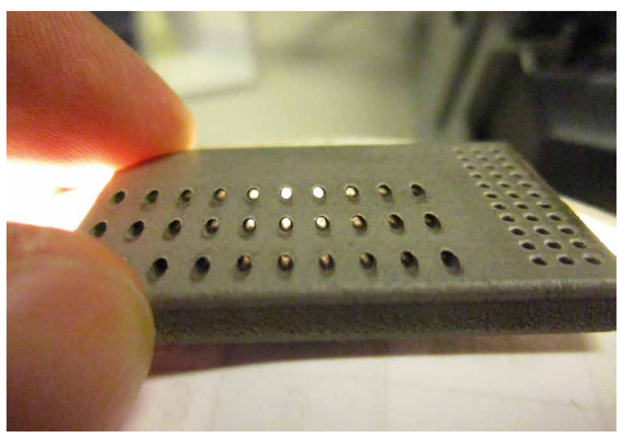
Laser MicroJet system

Different LMJ systems are supplied by Synova for different end applications, with some more details in [4]. Each system consists of four key parts [5]:

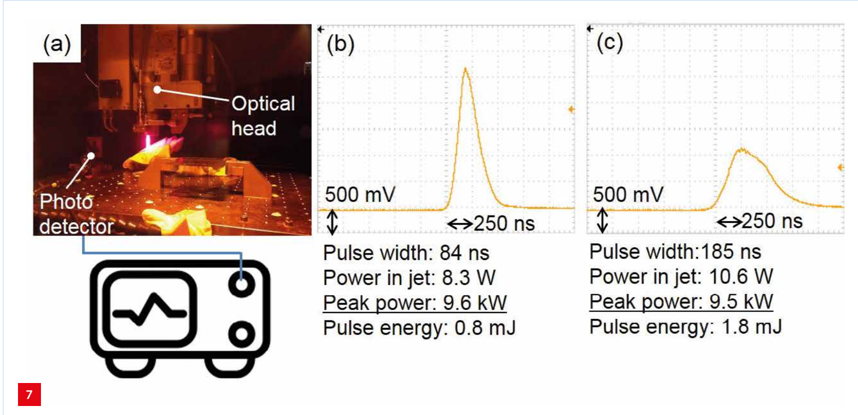
1. Laser source, which generates nanosecond laser pulses.
2. Optical head, which couples the laser into the water jet.
3. Integrated water system, which filters, deionises, degases, pressurises and controls the quality (resistivity and particle content) of the water supply.
4. Axes system, which varies from two up to five axes.



LMJ drilling holes in high-pressure turbine blades. (Image credit: GE Power)



Synova's MCS 300 LMJ system at Ter Hoek.



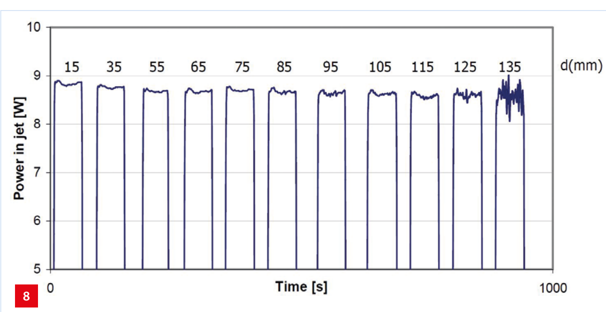
Laser characterisation.
(a) Set-up to measure the laser pulses.
(b) Measurement of a relatively short laser pulse.
(b) Measurement of a longer laser pulse.

The LMJ system at Ter Hoek is an MCS 300 series (3-axis) machine, which is Synova's LMJ technology integrated on a Makino machine platform (Figure 6). The position accuracy is ±1 µm in both the X- and Y-axis. The 3-axis machine enables high-precision metal and hard-material machining such as cutting, drilling and grooving. Together with Erowa-based workpiece clamping systems, which are widely used at Ter Hoek, it is possible to combine LMJ with EDM [V3] and precision electrochemical machining (PECM) [V4] technologies also available at Ter Hoek, without losing the workpiece reference.

Different nozzles with a diameter from 30 to 80 µm can be used, which results in a machined kerf width from 32 to 100 µm, respectively (the exact value is material- and process-parameter-dependent and even can be smaller than the nozzle diameter), and a working length of about 1,000 times the nozzle diameter. The associated jet pressure is between 50 and 500 bar, exerting negligible forces (< 0.1 N) on the workpiece.

Laser characterisation

The system is working with a pulsed, frequency-doubled Nd:YAg laser with a maximum output power of 50 W (single cavity) at 532 nm (green laser). Besides the laser power, the frequency (6-60 kHz) and pulse width (70-500 ns at FWHM) of the pulsed laser can also be tuned to the application. To characterise the laser after coupling with the water jet, the waveform of the pulsed laser was acquired via a photo detector (DET10A, 200-110 nm, ThorLabs) and displayed on an oscilloscope (TDS 2012C, Tektronix) with the set-up shown in Figure 7a. A laser power probe (Fit, Laserpoint) was placed underneath the jet to measure the laser power.



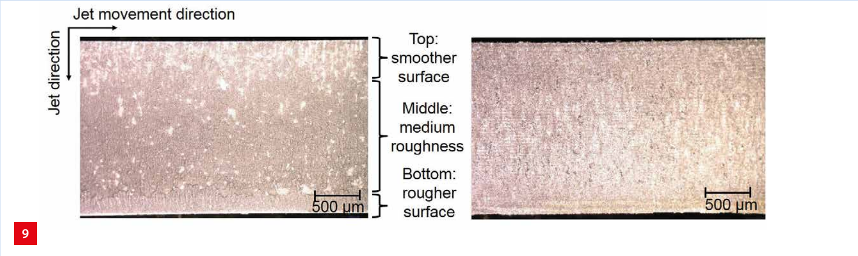
Measured laser power for a given jet length from 15 up to 135 mm, with an 80-µm-diameter nozzle (laser settings: 5 kHz, 10 W). (Image credit: Synova)

Generally, a certain level of peak power is needed to be able to ablate the material and longer pulses will lead to a higher process speed. However, providing sufficient peak power, short pulses will minimise the heat damage. An example is shown in Figure 7b (shorter pulses) and Figure 7c (longer pulses), where the two pulses have different pulse width and energy, but the same peak power.

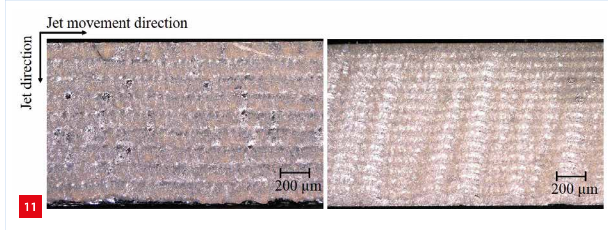
Regarding the laser power evolution along the jet working length, tests have been done at Synova; the results are shown in Figure 8. It can be clearly seen that the laser power is rather stable at increased jet length, which confirms the theory of total internal reflection of the laser beam at the water/air interface, until at 125 mm the laser power starts to fluctuate, indicating that perturbations (jet instability) are becoming more dominant. As a consequence, the laser beam maintains a constant diameter up to this working length, which results in highly parallel kerfs.

Characterisation of kerf surface

Depending on the workpiece thickness, laser power and process speed, the workpiece can either be cut in a single-/mono- or a multi-pass strategy. In a multi-pass strategy, the



Comparison of the kerf surface of a 2-mm-thick stainless-steel sample machined with the mono-pass (left) and multi-pass (right) strategy.



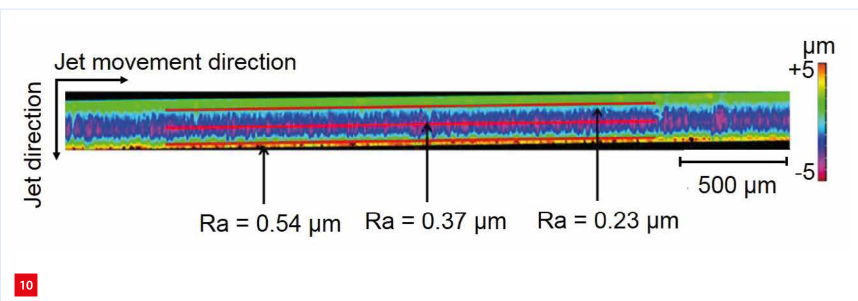
Comparison of the kerf surface of a 1.4-mm-thick silicon sample machined with the multi-pass strategy; left and right with different laser power and process speed values (see the text).

material is cut through after several reiterations of the same tool path with each pass cutting a section of the total thickness, similar to a milling process.

Figure 9 shows an example of the same workpiece (2-mm-thick stainless-steel sample) machined following the two different strategies, with the same laser parameters, except for a different process speed. Both photos were taken by a digital microscope (Keyence VHX5000), also for Figure 11. With a mono-pass strategy, the laser needs time to cut through the material at each position along the jet movement direction.

The processed surface can be characterised in three different sections along the jet direction, as shown in the left figure:

- the top section where the laser enters the material, showing a relatively smooth surface;
- the middle section, where the laser is fully contained in the material and high-efficiency cutting is guaranteed; on the other hand, redeposition of molten material occurs in this section probably due to insufficient local cooling by the water jet, which in turn increases the surface roughness;
- the bottom section where the laser cuts deep into the material; the water jet becomes less stable and may deviate from the ablation front, which causes jet oscillation and generation of vertical striation (similar to abrasive water jet machining) – as a result, the surface becomes even rougher and less material is removed in this section, which yields a concave barrel shape, as can be seen more clearly in Figure 10.



Topography measurement of the kerf surface of a 0.2-mm-thick brass sample machined in mono-pass, with the profile roughness R_a indicated at three different locations [6].

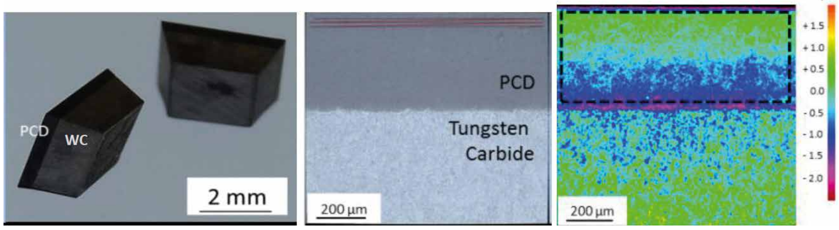
Please note that the surface topography after mono-pass as seen in Figure 9, left, is more common for ductile materials than for hard materials, and with further process-parameter (laser power and process speed) optimisation for surface quality, both middle and bottom sections can be smoother.

Similar observations can be derived from the topography measurement of a 0.3-mm-thick brass sample processed with the single-pass strategy, as shown in Figure 10, which was taken by a 3D optical microscope (Alicona Infinite-FocusSL), also for Figure 12, middle and right. The surface processed with the multi-pass strategy (Figure 9, right), on the other hand, clearly shows the different tracks after each pass. Despite the different surface sections as discussed for Figure 9, left, overall the mono-pass strategy results in a smoother surface than multi-pass due to the absence of the tracks as shown in Figure 9, right. However, the surface roughness produced by multi-pass is more uniform as each layer is cut under more or less the same conditions.

Unlike ductile metals, brittle materials such as semi-conductors and ceramics, are more prone to material damage such as chipping. Figure 11 shows the kerf surface from the same silicon sample, cut with a multi-pass strategy, but now with different process parameters: the left one with higher laser power and lower process speed, and the opposite for the right one. As a result, fewer but bigger tracks are seen in the left one, more but smaller tracks in the right one. Chipping is clearly visible at the back/exit side of the material in Figure 11, left.

To reduce the chipping, generally the process speed has to be increased to reduce the depth of cut per pass. Higher laser power on the other hand, will increase the heat input, and redepositioning of the debris on the cut walls is also seen in Figure 11, left, which will deteriorate the quality of the kerf surface. In order to obtain a clean kerf surface with less chipping, relatively short laser pulses similar to the ones in Figure 7b have to be chosen together with an appropriate process speed.

Besides cutting a single material, Figure 12 shows the kerf surface of a polycrystalline diamond (PCD) tool with tungsten carbide (WC) substrate, cut by a 5-axis LMJ



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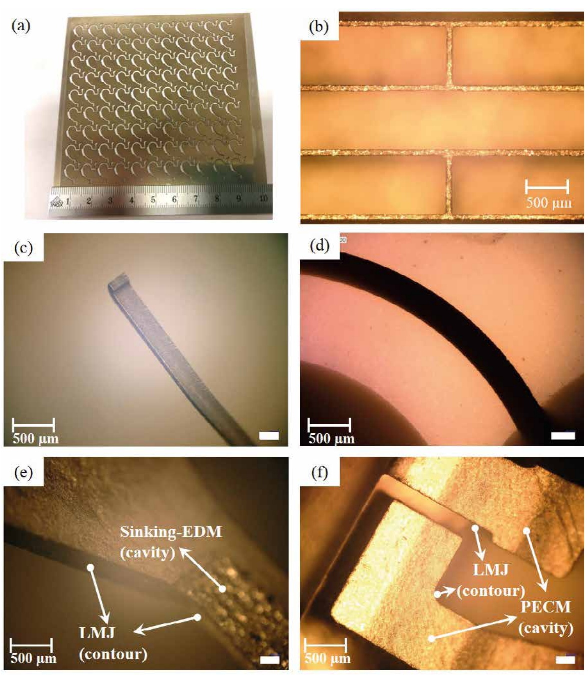
PCD tool with WC substrate cut by LMJ [5].

system, with the kerf surface shown in the middle and the topography measurement on the right, with the marked region indicating the PCD layer. There is a dark blue region near the bottom of the PCD layer, which is probably caused by chipping; further beneath there is a magenta region at the interface, which indicates some loss of cobalt as the binding material, probably due to the instability of the jet when crossing the interface.

Despite the issue at the interface, the sample has been cut through in one set-up; the surface roughness (S_a, measuring field 1 x 0.35 mm^2, vertical resolution of 50 nm and lateral resolution of 2 µm) of the PCD layer and the WC layer is 0.20 ± 0.02 µm, and 0.40 µm, respectively. The same sample has also been cut with wire-EDM; the surface roughness (S_a) measured on the PCD layer is 0.29 ± 0.02 µm, and 0.31 ± 0.01 µm on the WC layer, which is comparable to LMJ. The process speed of LMJ however is six times that of wire-EDM [5].



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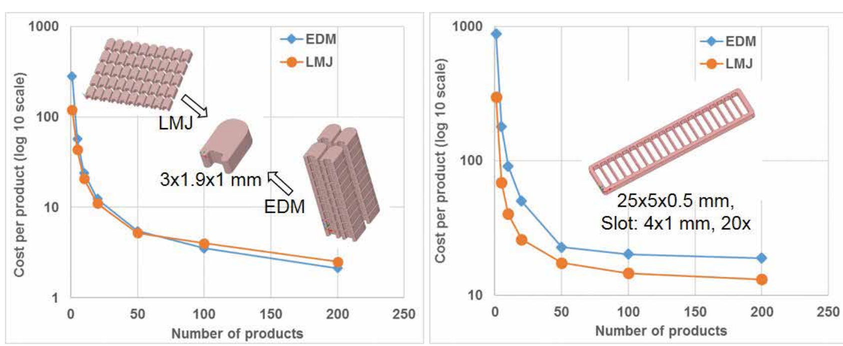
Products made by LMJ at Ter Hoek.
(a) Stainless-steel rest material after functional parts (11x9 pieces) have been cut off.
(b) Stainless-steel grid with 60 µm wall thickness.
(c) Stainless-steel gripper for medical application.
(d) Alumina ceramic piece with 6 mm thickness.
(e) Tungsten piece made with LMJ and die-sinking EDM.
(f) Titanium piece made with LMJ and PECM.

Applications at Ter Hoek

The application of LMJ technology at Ter Hoek is twofold: the application of LMJ itself including process development and validation, and finally series production; and the integration of LMJ with EDM and PECM technologies.

Various materials have been tested, including metals, ceramics/hard materials, gemstones, semiconductors and composites. The application areas include the semiconductor, electronics, automotive, aerospace, medical and watchmaking industries, as well as tool manufacturing and micromachining in general. Regarding the applications at Ter Hoek, LMJ is found to be an ideal technology in the following cases:

- Cutting small but complex functional parts from thin sheet metal (from 0.02 up to 2-3 mm) with feature sizes down to 50 µm and precision within a few µm. Examples are shown in Figure 13a and 13b.
- Precision drilling of small holes in thin sheet metal up to a certain aspect ratio.
- Creating flexible mechanisms, such as springs, in thin sheet metal. An example is shown in Figure 13c.
- Precision cutting of other materials aforementioned with a thickness up to a cm, particularly for insulating materials which cannot be processed with EDM. An example is shown in Figure 13d.
- Integration with die-sinking EDM and PECM technology for cutting precision contours, ideally suited for prototypes and small and medium-sized batch production; and with wire-EDM for the precision manufacturing of small start holes. Examples are shown in Figure 13e and 13f.



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Two examples of the cost-per-product evolution for LMJ and EDM; the product on the right needs more start holes for wire-EDM to cut each slot.

Though the working length of LMJ is rather high, it is found to be more efficient when processing thinner metal sheets, because the effective process speed (the process speed divided by the number of passes when applicable) drops dramatically with the increase of the material thickness. On the other hand, LMJ is rather flexible and ideal for making prototypes.

Additionally, a calculation module has been made in-house to compare the cost for making the same product between LMJ and EDM. EDM consists of hole-drilling EDM and wire-EDM steps, with the former step making the start holes for threading the wire for the latter step. Two examples are shown in Figure 14, where the right one needs more start holes for wire-EDM to cut the slots. In both examples, it is clear that the cost per product for EDM is initially higher than for LMJ due to the higher set-up cost including start hole drilling.

Beyond a certain product quantity (tipping point between 50 and 100 pieces), EDM is winning in the left example because multiple plates can be stacked to be machined at once as illustrated in the figure, as a result of which the running cost is reduced. LMJ, on the contrary, has a lower set-up cost but a higher running cost as products are not made in stacks as with wire-EDM. However, when lots of start holes are needed for wire-EDM, as in the right example, the tipping point has virtually vanished. To conclude, depending on the product geometry, LMJ can be more economical than EDM for both small and large product quantities.

Conclusion

LMJ is a hybrid technology combining laser and water jet technology, enabling certain advantages as compared to conventional dry laser technology, including longer working length, precise and parallel cut, better local cooling and hence a smaller heat-affected zone, and last but not the least, less particle deposition and contamination.

Ter Hoek has started to explore the process of LMJ and provides its service to the high-tech industry since 2014, for both prototyping and serial production. LMJ is found to be more competitive than wire-EDM technology when producing small but complex parts in thin sheet metals. Besides the application of LMJ alone, focus is also put on integrating LMJ with EDM and PECM technologies also available at Ter Hoek. Furthermore, calculation modules have been made to have a quick comparison of the cost per product between LMJ and EDM, to offer a better price for the customer.

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[6] Bai, Y., et al., "Reducing the Roughness of the Kerf for Brass Sheet Cutting with the Laser MicroJet® by a Systematic Parameter Study", *Proceedings Lasers in Manufacturing Conference 2015*, contribution 154, 2015.

VIDEO

[V1] Synova Laser-MicroJet in 2 Minutes,
www.youtube.com/watch?v=Q_lRaONosxc

[V2] Ter Hoek LMJ animation,
www.youtube.com/watch?v=FNSfRC6kYdU

[V3] Ter Hoek EDM animation,
www.youtube.com/watch?v=TzkiCb-pLC4

[V4] Ter Hoek - Precision Electro Chemical Machining (PECM),
www.youtube.com/watch?v=p_uW_Y6relY