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From jewels to quantum, challenges in Laser MicroJet® Cutting

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Abstract

By cutting and sawing of natural diamonds into brilliants, Synova has been a significant provider of diamond cutting systems through its water jet-guided laser technology. In jewelry, the Laser MicroJet® (LMJ®) is allowing the cutting of natural stones of ever-growing thickness with low damage and increased yield. The increasing cost reduction and quality of lab-grown diamond (LGD) over recent decades has enabled an industrial exploitation of diamond's outstanding hardness, thermal conductivity and very broadband transmission for industrial sectors such as wear resistant coatings, tool making, super abrasives, optics and sensors. Today, LMJ®'s unique value proposition and versatility as cutting tool serves as a catalyst for industrial breakthroughs with LGD diamonds, including cutting of quantum crystals, coring and slicing of LGD blocks, diamond turning and shaping of 3D-geometry. We present a retrospective of technical challenges for the LMJ® in the world of diamonds by showcasing the most challenging and most important machining applications.

Keywords: water jet guided laser; diamond; natural; synthetic; CVD; LGD; jewel; quantum; optics; processing

1. Introduction

The water jet guided laser (WJGL) technology has been present in the industrial micro-machining landscape since 1997 when the technology was pioneered by Synova S.A. from the laboratories of EPFL (Richerzhagen, 1994). The process consists in generating a centimeters long, hair-thin laminar water-jet and use it as a light guide for a high-power (20-400 W) green, nano-second DPSS laser. The water jet guides the light towards and through the workpiece, the laser pulses melt, vaporize and eject the material and the workpiece is then cooled in-between pulses by the water jet (Liao, 2021). The process is therefore accurate and enables narrow, vertical cuts in hard-to-machine materials of up to 30 mm thickness and more (Fig.1).

The technology is well suited to the processing of metal alloys (Subasi, 2021), ceramics such as AlN or c-BN, semiconductors such as Si and SiC, composites such as carbon fiber-reinforced polymers (CFRP) and ceramic matrix composites (CMC) (Elkington, 2022), as well as diamond (Shankar, 2015).

The Laser MicroJet® has pierced initially in the semiconductor industry, (Sibailly, 2004) (Snowdon, 2006) and has since made strides in different markets including the watchmaking industry (Shankar, 2012) (Bai, 2015), the aerospace industry (Shankar, 2017) and (Subasi, 2023) but a breakthrough was its entry in the diamond market starting in 2010.

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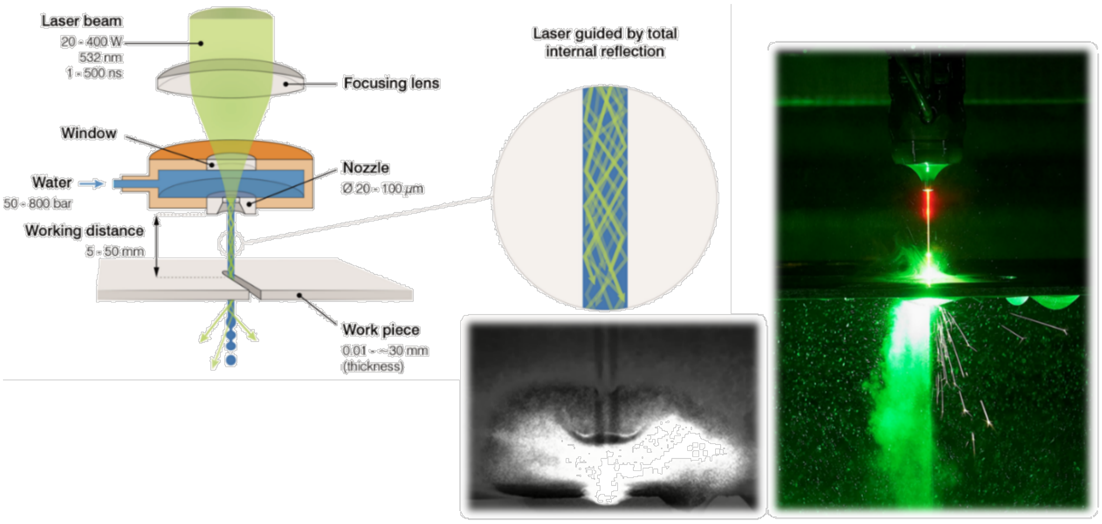


Fig. 1. Principle of the Laser MicroJet®.

In this application review, we reflect on how the natural diamond market has guided a gradual upskilling towards more ambitious undertakings. We will then present some of the key technical challenges encountered and resolved in the LMJ® processing of diamond. Finally, we will look to the future of LMJ® applications, and how the versatility of the technology can be leveraged in diamond applications ranging from cutting tools to quantum sensing.

2. Versatility from tables to jewels

Since the first diamond cutting applications in 2010, the needs of the industry have led Synova to develop its product and know-how from 1 to 5 axis machining and to the whole process chain. We detail in the following how this up-skilling has led to increasingly ambitious processes.

2.1. Light-matter interaction: how the LMJ® cuts diamond

The need for high transmission of the laser light in water makes the use a green laser favorable. This in turn limits the ability of the system to process transparent materials, with diamond being an exception, due to the unique physical mechanism of light-matter interaction when using pulsed lasers.

During the initial green laser pulse exposition, the diamond first undergoes graphitization (Mouhamadali, 2020), making the layer highly absorbent to the laser radiation and allowing the pulse to vaporize a volume of the material (Fig.2).

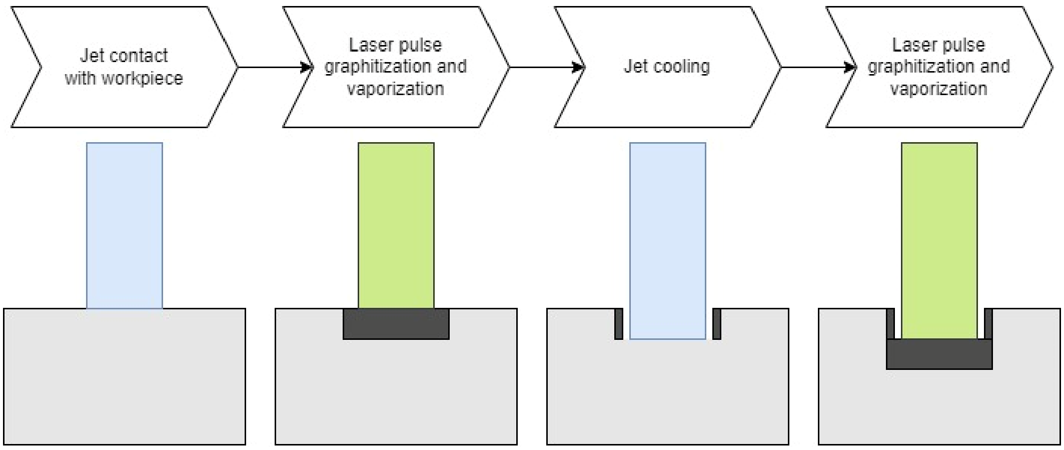


Fig. 2. Cycle of laser-induced graphitization and ablation with the LMJ® process.

The depth of the graphitized layer based on laser pulse duration has been calculated and measured (Fig. 3). The use of the Laser MicroJet® system with pulses longer than 100 ns leads to high depth of graphitization and therefore high throughput of the process. Where an ultra-short pulse laser will be used to lower heat damage on the diamond, the LMJ® circumvents this limitation with the cooling effect of the water jet.

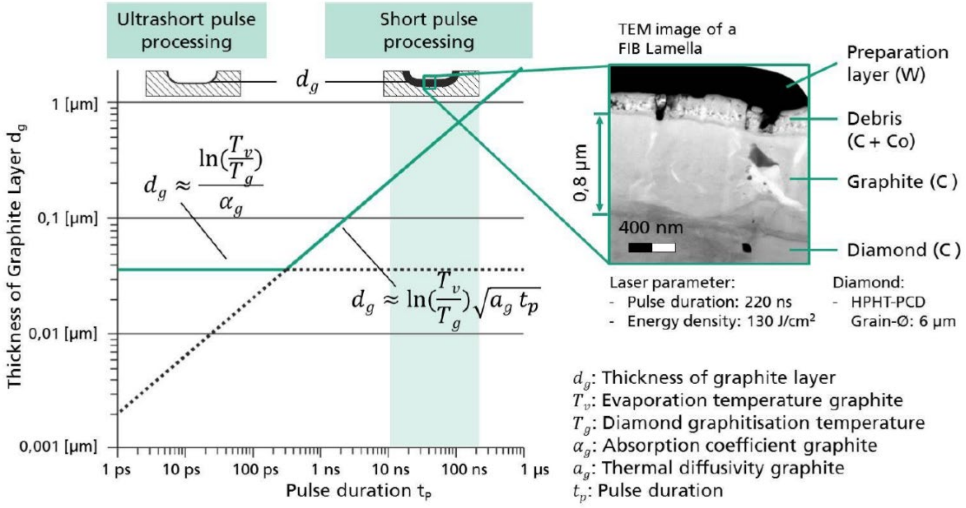
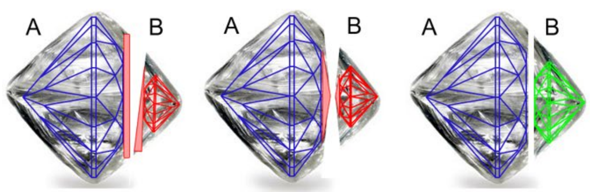


Fig. 3. Effect of a nano-second laser pulse on the depth of graphitized layer on diamond (Hermani, 2015), (Kononenko, 2005).

2.2. Sawing as a breakthrough application

The application of the LMJ® to diamond has been pioneered by the sawing of natural stones. Within a single stone, several brilliants can be planned for cutting and polishing, for which the stone has to be separated (sawed) precisely. The unique value proposition of the LMJ® process is the completely straight and parallel cutting (no V-shape), which enables single direction cuts with reduced need for rectification (Fig.4). Moreover, volume loss (or mass loss) is reduced, especially with larger stones, thanks to the narrow cutting kerf of typically 50 microns over the entire cut depth.



Conventional Laser
Single direction & bi-direction

Mass-loss
Need rectification

LMJ®
Single direction

Low mass loss
No rectification

Size	22.9 cts	38.8 cts	63.9 cts
Cutting depth	12 mm	15 mm	18 mm
Cutting time	45 min	56 min	69 min
Weight loss	0.66 %	0.63 %	0.43 %

Fig.4. Geometry of conventional and LMJ® cutting and examples of planned cuts and their results for the LMJ®.

The typical cutting speed and mass loss for sawing larger stones in two halves is shown in Figure 5. Additionally, the reduced heating provided by the water jet prevents the thermal cracking of stones.

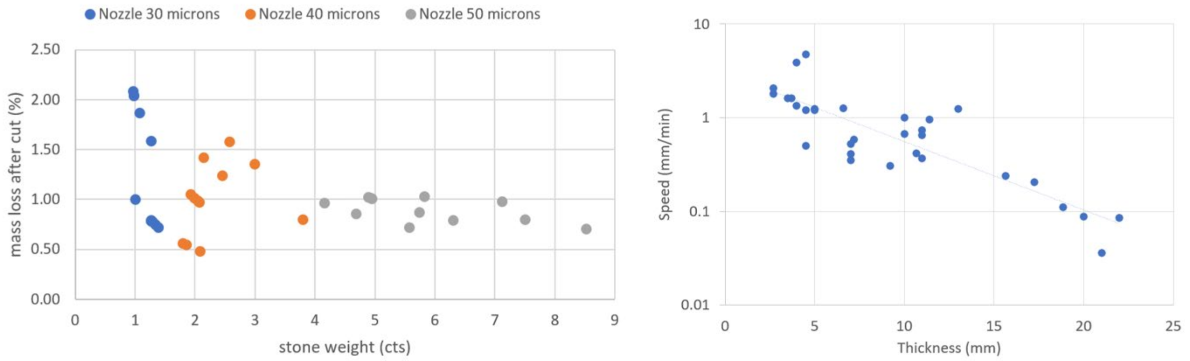


Fig. 5. Measured mass loss after cut vs. stone weight (left) and cutting speed vs. thickness (right).

The efficient and precise cutting of larger stone has enabled more ambitious shaping operations as seen in the next section.

2.3. From sawing to round brilliants

Traditionally, the stones which were sawed in several pieces are then polished to finished brilliants in a long and manual process, by grinding away all the material surrounding the finished facets in the natural stone.

Over the years, the process chain for the LMJ® was streamlined, gradually advancing the cutting of jewelry diamonds towards producing facetted stones ready to polish, such that the cutting process greatly reduces the effort and time of the polishing. Synova's know-how and machine capabilities enabled moving from sawing (1 axis) to bruting (2 axis), coning (4 axis) all the way to fancy faceting (5 axis) (Fig.6).

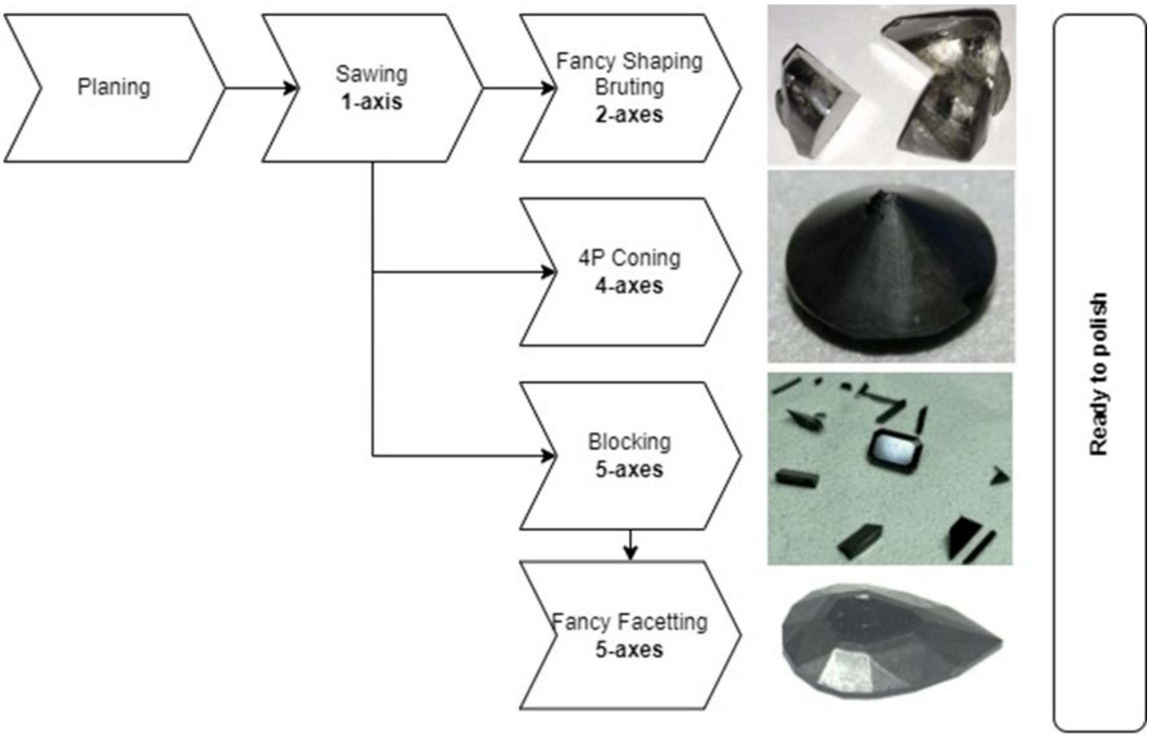


Fig. 6. Evolution of processing capabilities in the jewelry sector.

3. Performance from challenges to solutions

As seen in the previous section, the complexity of the parts being processed has gradually increased. The evolving challenge came with some key issues that had to be resolved such as brilliants with smaller facets, automating a process sequence and reaching industrial relevance for mass produced LGD.

3.1. Facetting ever smaller facets

Increasing the number of facets of a diamond towards the standard 57 facets brilliant shape has led to shallower angles of attack for the LMJ® with regards to the cutting surface, which in turns leads to increased sensitivity of the process to perturbation. This can result in deep striations (Fig. 7 (left)). Parametric optimization enables the process to be striation free (Fig. 7 (right)).

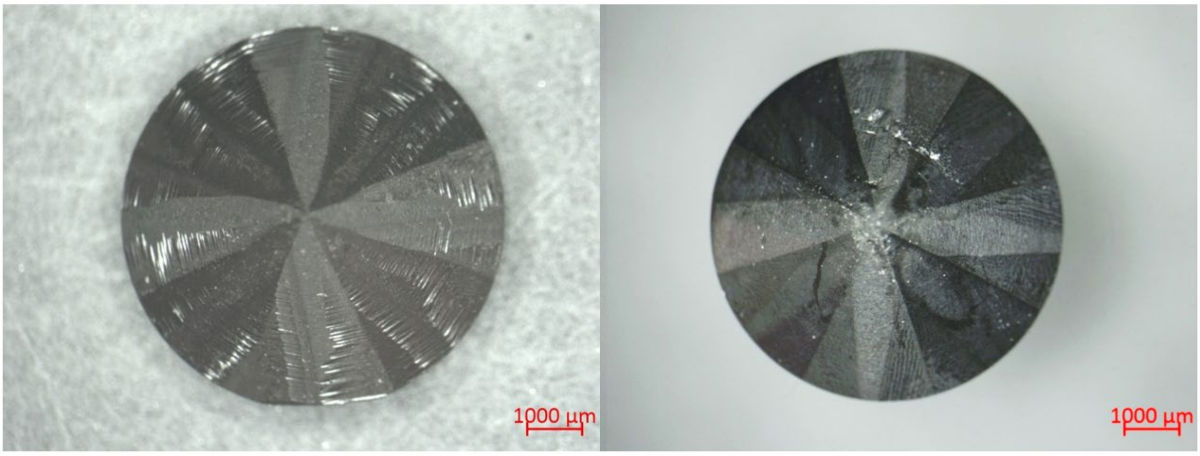


Fig. 7. Round brilliant showing deep striations (left) and corrected, optimized process (right).

The challenge of processing ever smaller facets has led to a scalable know-how in cutting smaller and more challenging geometries. However, the variable thickness encountered in complex cutting sequences can make the stone processing time long and involves the operator presence to guide the sequence.

3.2. Automating cutting sequences

As the cutting processes become longer with more operations on the same part, the challenge of sequence automation becomes primordial. Synova developed, in collaboration with Fraunhofer-IPT a proprietary BreakThrough Sensor (Braunmuller, 2021). capable of detecting a completed cut (Fig. 8). As such it becomes possible to automate the operation even when cuts of different size and duration are performed in sequence.

The addition of the breakthrough sensor has led to an overall decrease in wasted cutting time of typically 30%, due to reduced empty processing time and removed safety times where the operator has to be present.

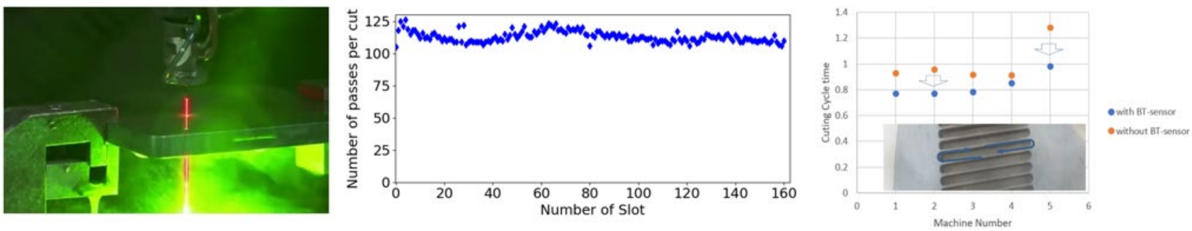


Fig. 8. Breakthrough detection (left) leads to upwards of 15% time gain on a cutting sequence (middle) and overall 20% on several machines running in parallel (right).

3.3. First industrial entry into LGD

Lab Grown Diamonds (LGD) coming from two distinct industrial processes (HPHT, CVD) have been around for decades but the increased quality, size and available volumes have pushed them into the mainstream jewelry market (Fig. 9). Consequently, the whole synthetic diamond supply chain (from growing to finished part) has grown in maturity drastically.

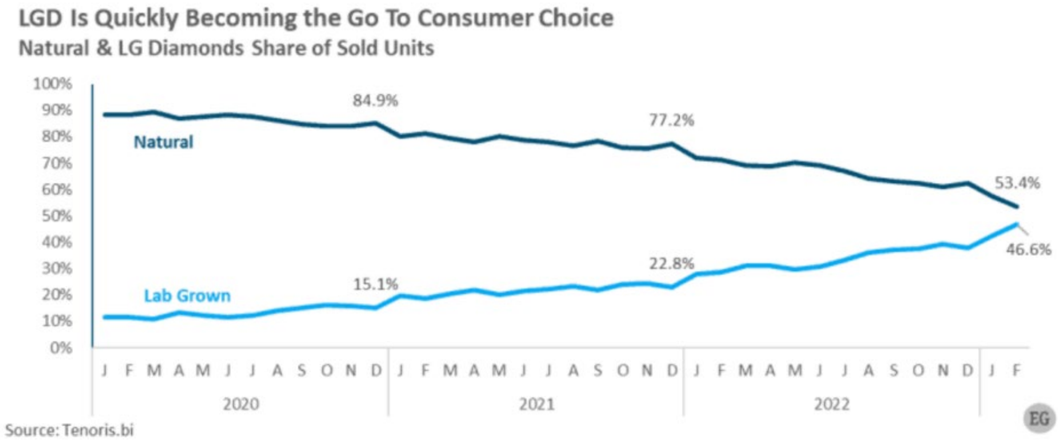


Fig. 9. Demand evolution for diamond, natural and LGD, from 2020 to 2022 (source: Tenoris.bi & EdahnGolan).

The accumulated experience through the jewelry industry, leading to finer, more complex cutting, higher throughput, and automation, as well as increased know-how have made the LMJ® technology ready for the requirements of the industrial market.

For LGD, the challenges are different. They include the separation of in-homogeneous graphitized growth (coring), as well as the slicing of stones into plates, which can be reused for growing new diamond crystals or to manufacture diamond based devices (Fig.10). The unique value proposition of the LMJ® is the ability to perform all operations in a single machine configuration, and to be able to cut thin slices in increasing stone sizes, without increasing the kerf width (or volume loss) thus increasing the number of slices per stone considerably (yield).

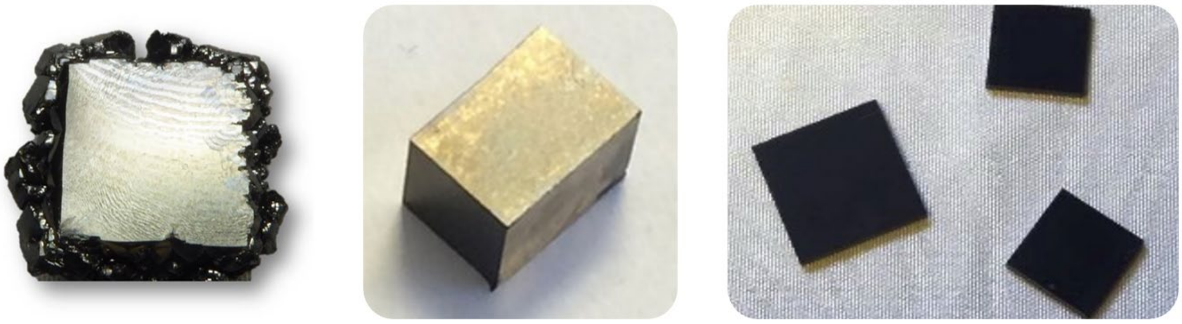


Fig. 10. LMJ® cutting from as grown CVD diamond (left) to clean crystal (middle), to straight plates (right).

As shown in Fig. 5 (right), the cutting process has been tested for diamonds more than 20 mm thick, an example of such a plate cut is shown in Fig. 11, with the corresponding roughness of the as-cut piece.

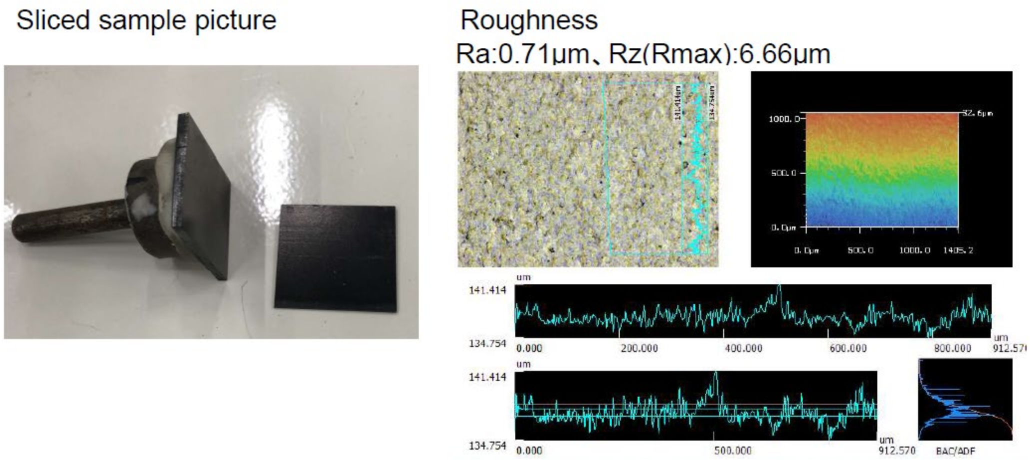


Fig. 11. Example of a 20mm thick CVD diamond cut in a single direction (left) and roughness measurements (right).

The typical resulting surface shows Ra 0.1 to 0.8 microns and the typical graphitized layer can be removed within a single micron of polishing. Alternative post processing methods have been developed to de-graphitize the processed parts, using chemical, thermal (Cobb, 2020) and mechanical operations, such as sand-blasting or direct polishing.

The increasing availability of LGD for industrial applications has led to more and more companies and industries developing devices and parts that need to be processed efficiently and accurately.

4. Future applications

As described above, the technology is being put through its paces towards the original vision for the LMJ® of highly versatile and efficient processing of complex features. In the following we review some of the more unique applications enabled by the Synova systems.

4.1. Tooling

Starting in 2010, and again in 2015 (Richmann, 2015), Synova has been developing 5-axis processing of cutting tool edges of polycrystalline diamond (PCD) backed by tungsten carbide (WC) (Fig. 12 (left)). New applications in the tooling sector have come into focus, such as the processing of as-grown CVD diamond disks into functional cutting wheels (Fig. 12 (right)) for the dental or medical industries.

Fig. 12. A cutting tool edge (left) and a diamond cutting wheel (middle and right) as-processed.

4.2. Hole drilling

Other applications demonstrating the versatility of the technology regard hole drilling, which can be of interest for the jewelry industry as much as for the industrial applications. Several mm deep holes, rods and tubes can be processed (Fig.13).

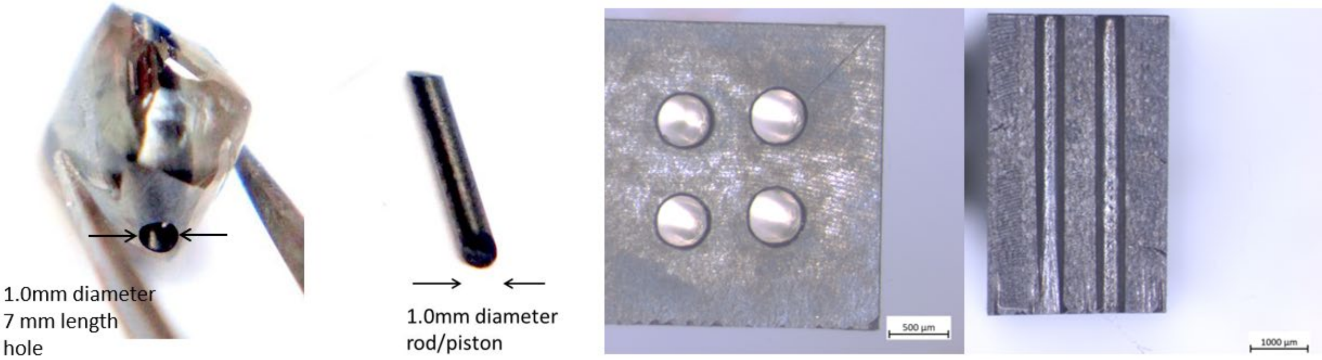


Fig. 13. Examples of hole drilling in natural (left) and CVD grown diamond (right).

4.3. DNV and Specialty diamond

With the considerable advances in technology readiness for LGD diamond growing, specialty diamonds are emerging with high potential for changing several industries. From ultra-pure single-crystals, boron doped for electronic applications and NV-center doped for quantum applications (Nebel, 2020), these materials all require fine post-processing to make them ready for integration into devices such as sensors and quantum computers. Synova has produced some demonstrators of quantum resonators from design to fully polished (Fig. 14). The straight cuts provided by the LMJ® process considerably simplify the polishing process.

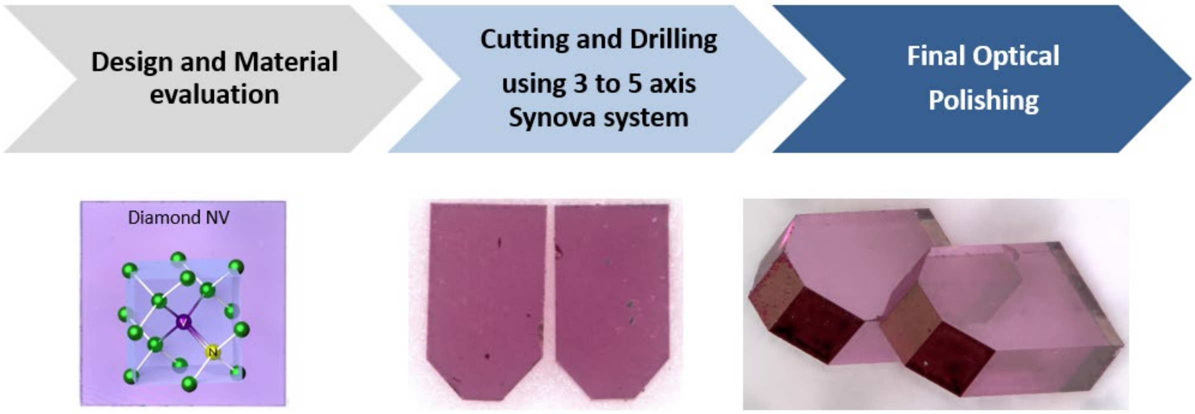


Fig. 14. From quantum active material to optically finished quantum resonator.

The industry is still evolving with many startups in the field developing their product offering and device manufacturing steps. While it will certainly not be useful for all specialty diamond applications, the inherent advantages of the LMJ® can accelerate some applications in the industry.

4.4. Specialty optics

In the context of process versatility, a further capability has been developed recently, enabling the precise turning of parts with the LMJ® (Moingeon, 2021). While the first applications on the topic concerned profiling of cutting and grinding wheels made of diamond composites or super-abrasives, a recent project focuses on the ability to LGD or other hard materials into optics for specialty applications using X-rays or neutron beams. The complex lens arrangements are well suited for accurate and freeform processing on materials of 0.5 mm up to 6 mm from the exterior via turning (Fig. 15 (left)) and from the interior via multiple structure drilling and cutting (Fig. 15(middle and right)). We expect the LMJ® to enable the manufacturing of larger lens arrays, thus enabling more resilient optics capable of shaping wider beams.

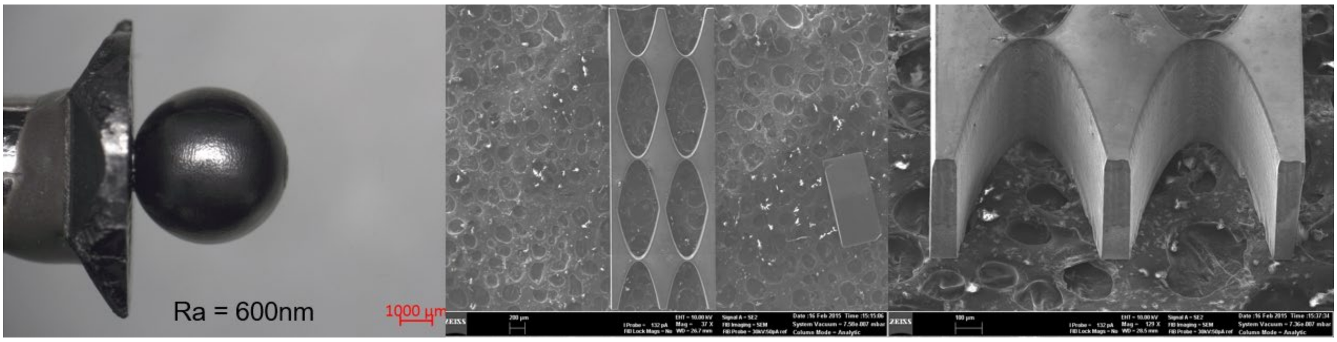


Fig. 15. A LMJ® turned CVD diamond sphere (left), and an example of a monolithic diamond Compound Refractive Lens (CRL) (middle and right).

5. Summary and outlook

As Synova celebrated its 25th anniversary in 2022, this contribution presents a retrospective on the evolution of diamond processing by LMJ®, including both market challenges, technical opportunities, together with an evaluation of how they allowed Synova to grow its know-how and offering in the evolving diamond market.

The jewelry industry has been the main commercial driver to leverage the inherent properties of the LMJ® into efficient and challenging cutting operations. From 1 to 5 axis, Synova has developed its capabilities from simple cuts to complex jewels. We briefly discussed the underlying materials science involved in laser processing of diamond, followed by key technical challenges encountered and solved regarding reliability, throughput and quality.

The acquired versatility has translated well to the new trends in industrial Lab Grown Diamonds and the specialty applications they enable, from tooling to quantum and even particle beam optics.

There is no doubt a long road ahead for the technology to become a staple of efficient, precise manufacturing in applicable industries and the panel of possibility remains wide in the era of advanced photonics.

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