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Water jet guided laser as a versatile turning method for industrial applications

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Abstract

The Laser Microjet® technology couples a nanosecond pulsed Nd:YAG laser into a thin cylindrical water jet. It comes with numerous advantages such as a reduced heat affected zone and a parallel energy beam over several centimeters. Laser turning is in high demand to process hard or fragile materials allowing the production of complex solids of revolution. However, conventional laser must still contend with heat management, as well as the throughput needed to ablate the whole volume. The LMJ technology can both cut-out large section in facets as well as fully turn the surface by ablation. Effective and efficient strategies of roughing and finishing become therefore possible and can yield high throughput. A surface roughness with Ra as low as 0.2µm can be reached. This paper presents several water jet guided laser turning strategies and their implementation in challenging industrial turning applications.

Keywords: Laser; water jet; turning.

1. Introduction and Motivation

The Laser MicroJet (LMJ) technology combines the efficient machining of an Nd-YAG pulsed nano-second laser (20 to 400W) with a micrometric (20 to 120µm) cylindrical water jet (see Fig. 1). Due to the cooling capabilities of the water and the straightness of the laminar jet over several centimeters, LMJ cutting results in high quality vertical kerfs (Richemann, 2014). Hard and sensitive material, such as metallic alloys, ceramics, CMCs, and high aspect ratio workpieces can therefore be efficiently processed. Supported by several sensing technologies (especially breakthrough detection and jet stability detection), the LMJ is being used in industrial

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production processes but also as a highly versatile tool for cutting, drilling and simple milling operations, while turning has been a recent development focus.

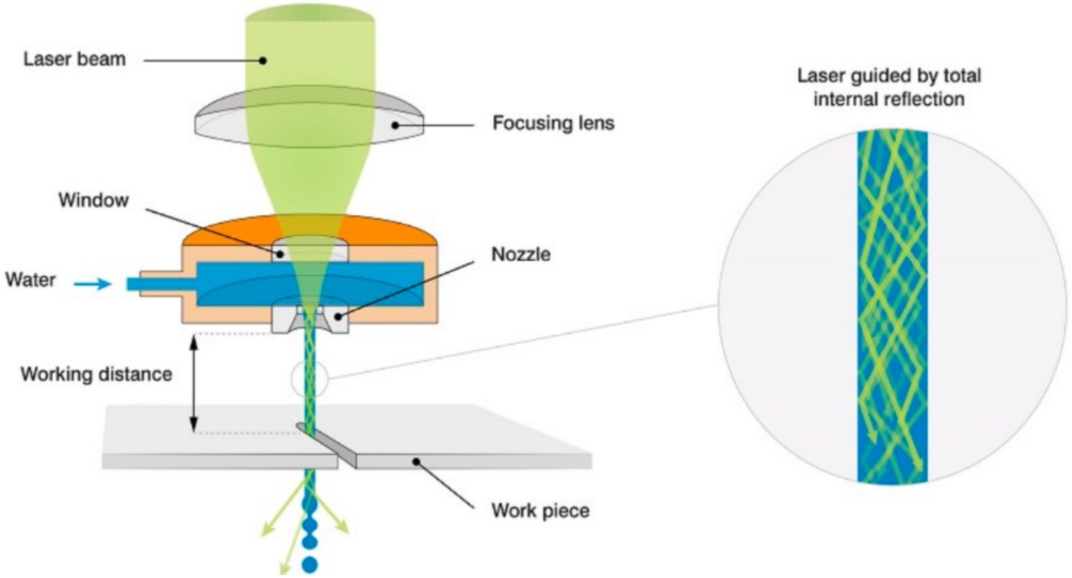


Fig. 1. Principle of the Laser Microjet

Conventional turning even when assisted by ultrasonic vibrations (Muhammad, 2014), or a laser source (Kim, 2011), encounters limitations due to workpiece accessibility or brittleness. On such parts, energy beam technologies emerge as a serious contender as low to no mechanical stress is applied to the sample (Ackerl, 2020). Moreover, they allow the generation of complex shapes with small details, high precision and surface quality in a wide range of materials difficult to machine by conventional methods. Low Material Removal Rates (MRR) is however a factor limiting the acceptance of such technologies.

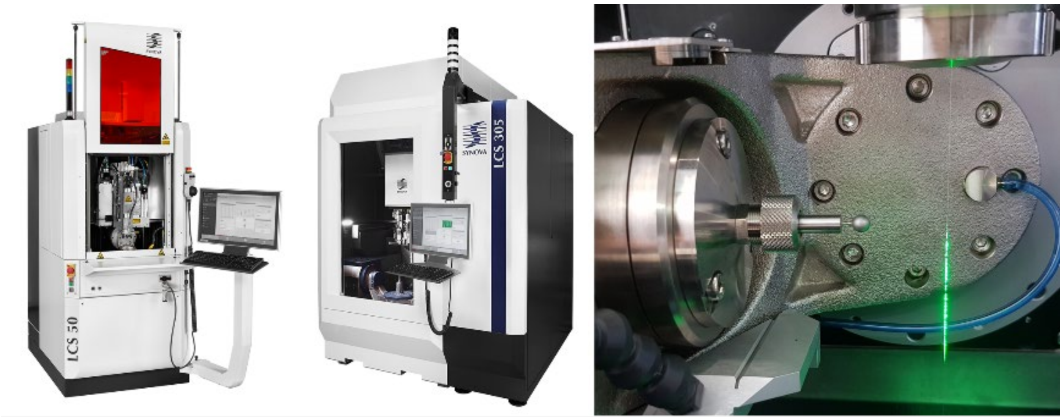
The objective of this paper is to demonstrate new turning strategies enabled by LMJ that combines the benefit of energy beam processes while reaching higher effective MRR and a micrometric precision. Several applications (metal, diamond & composite) showcase its capabilities as a turning tool and the various strategies employed.

2. Materials and method

2.1. Material

The application highlighted in this article were performed on Synova’s 5 axis machines LCS 50 and LCS 305 (see Fig. 6. a and b). The LCS 50 has a working volume of 50 x 50 x 50mm and allows rapid processing of small samples with its robust chuck system. The LCS 305 has a working volume of 500 x 380 x 380mm and a micrometer precise HSK holder for precise processing of large workpieces. Both 5 axes systems can turn, cut, mill, and engrave samples to produce complex 3D workpieces and features.

Visual observations were made under a binocular, while roughness measurements are performed with an Alicona InfiniteFocus confocal microscopy system.

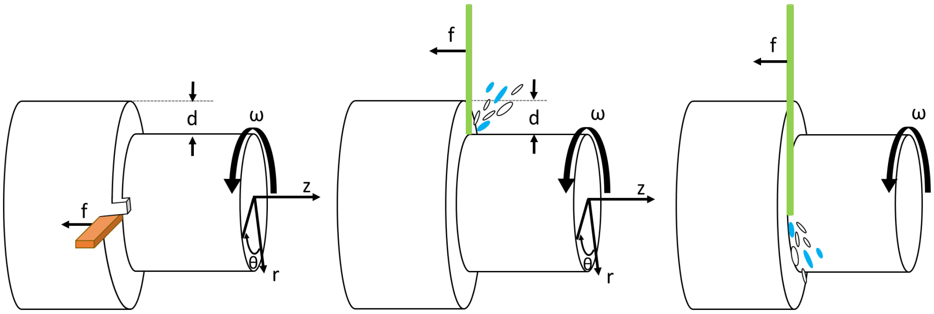


(a) (b) (c)

Fig. 6. LMJ turning machines and setup. (a) LCS 50. (b) LCS 305. (c) Steel sphere turned by LMJ clamped on an LCS 50.

2.2. Laser Microjet as a turning tool

LMJ used in turning operations shows several similarities with conventional processes. The key variables for the description of turning processes are described in Table 1. The workpiece is rotating at a given cutting speed *ω*, while both tools advance at a given feed *f* in the *z* direction removing a layer of material with a given thickness *d*. Conventional facing and grooving can also be performed by the LMJ in a similar approach.



(a) (b) (c)

Fig. 2. (a) Conventional turning. (b) LMJ turning, normal ablation. (c) LMJ turning, tangential ablation

Table 1. Conventional turning variables

Variable	Abbreviation	Unit
Cutting speed	ω	rad/s
Feed	f	mm/s
Feed per Revolution	f_n	mm/rev
Depth of cut	d	mm

As shown on Fig 2, LMJ turning can be performed with the jet normal (b) or tangential (c) to the workpiece surface. Normal ablation maximizes the intensity of the light transferred to the sample and therefore leads to high ablation rates. On the other hand, tangential ablation allows for a precise finishing. The light guiding water jet only ablates the material in contact with the thin jet, until all material possibly in contact has been ablated.

LMJ ability to cut straight and deep kerfs on the same machine allows for a new strategy to approach any rotational symmetry feature by faceting, see Fig 3. Successive partial cuts can be performed to reduce the diameter of a given sample without ablating the whole volume, generating large cut-outs. If necessary, a finishing step by tangential or normal ablation is added. The effective MRR is thus drastically increased as only a fraction of the workpiece volume is ablated.

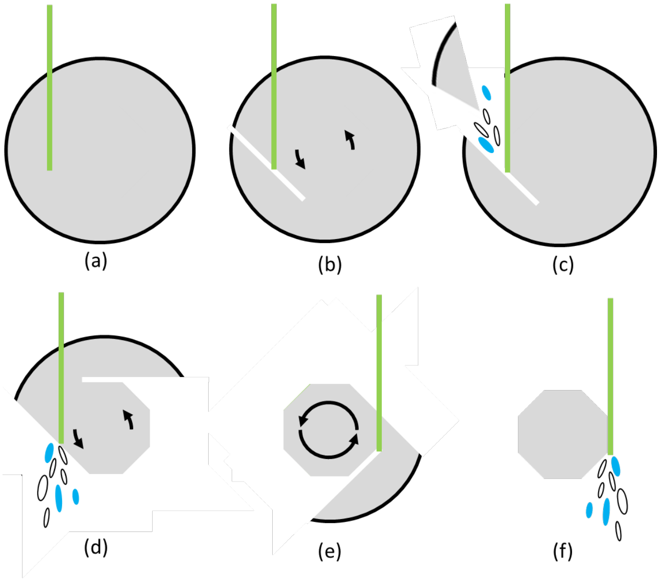


Fig. 3. Workpiece faceting (Front view). (a) A first partial cut is performed. (b) After rotating the workpiece, a second partial cut is performed. (c) A cut-out is ejected as the second kerf reaches the first one. (d) The process is repeated multiple times. (e) The last cut-out is removed faster from the other edge of the workpiece after rotating it by 180°. (f) A faceted solid is obtained.

The process is optimized to reach a given accuracy (or Tip length *Le*, defined as the largest radius distance between the faceted solid and the target diameter in Equation 5) in the smallest possible time, by maximizing an efficiency factor *Fe* described by Equation 1 below. The key variables for this optimization are explained in Table 2 and represented on Fig 4.

Table 2. Faceting variables

Term	Description	Abbreviation
Faceting angle	Angle in between two consecutive facets	α
Separation faceting angle	Limit angle at which facets do not overlap each other	α_{sep}
Workpiece outer radius	-	R
Post process radius	-	r
Cut depth for faceting	Depth of cut required so that partial cut kerfs overlap each other	L_C
Cut-off area	Area of a cross section of one facet	A
Efficiency factor	Efficiency of the faceting process, equal to the cut-off area divided by the cut depth for faceting	F_e
Tip length	Largest radial distance between the faceted solid and the targeted radius	L_e

$$F_e=\frac{A}{L_C}=\begin{cases}\dfrac{\frac{\alpha}{2}R^2-r^2\tan\left(\frac{\alpha}{2}\right)}{\sqrt{R^2-r^2}+r\tan\left(\frac{\alpha}{2}\right)} & \alpha\leq\alpha_{sep}\\[2ex] \dfrac{R^2\cos^{-1}\left(\frac{r}{R}\right)-r\sqrt{R^2+r^2}}{2\sqrt{R^2+r^2}} & \alpha\geq\alpha_{sep}\end{cases}\tag{1}$$

Where, based on geometrical considerations:

$$\alpha_{sep}=2\cos^{-1}\left(\frac{r}{R}\right)\tag{2}$$

$$L_C=\begin{cases}\sqrt{R^2-r^2}+r\tan\left(\frac{\alpha}{2}\right) & \alpha\leq\alpha_{sep}\\ 2\sqrt{R^2-r^2} & \alpha\geq\alpha_{sep}\end{cases}\tag{3}$$

$$A=\begin{cases}\frac{\alpha}{2}R^2-r^2\tan\frac{\alpha}{2} & \alpha\leq\alpha_{sep}\\ R^2\cos^{-1}\left(\frac{r}{R}\right)-r\sqrt{R^2-r^2} & \alpha\geq\alpha_{sep}\end{cases}\tag{4}$$

$$L_e=\begin{cases}r\left(1-\sqrt{1+\tan\left(\frac{\pi-\alpha}{2}\right)^2}\right) & \alpha\leq\alpha_{sep}\\ R-r & \alpha\geq\alpha_{sep}\end{cases}\tag{5}$$

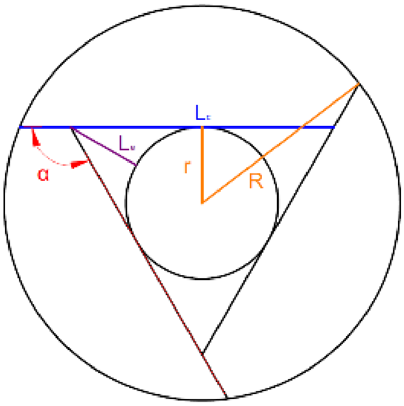


Fig. 4. Schematic representation of faceting variables

Faceting can be used as a roughing and/or as a finishing strategy. A large tip length value is acceptable for a roughing phase, leading to few facets, large cut-outs and a high effective MRR. As an example, to reduce the diameter of a rod from 6mm to 1mm, if 3 facets are cut with a 50µm diameter nozzle, the cut depth required for faceting is 3.8mm and the remaining tip length 0.5mm as shown on Fig 5.

This process results in the ablation and ejections of 98% of the volume while ablating only 2.1% of this volume. The effective MRR is in this specific case 46 times higher than the equivalent ablation only MRR. In a different manner, targeting a tip length smaller than 1µm by setting a small angle in between the facets works as a finishing step. It will result in a post process precision and quality that is on a par with other cutting strategies (see Fig 9 and 10).

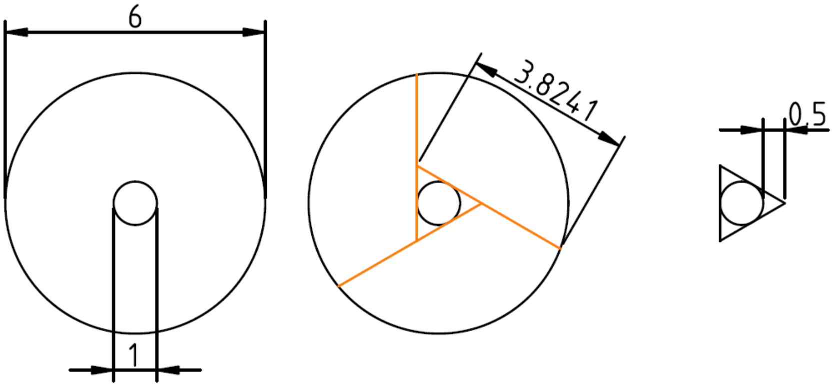


Fig. 5. Example of faceting as a roughing process, rod diameter reduction from 6mm to 1mm.

3. Application examples

3.1. Tangential ablation

LMJ turning was performed on a diamond-copper composite to obtain a half sphere shape, see Fig. 7. The sample was constantly rotated as the LMJ moved along the desired profile. As material was ablated, the waterjet became progressively tangential until the final shape was reached.

A surface roughness Ra of 1µm, measured perpendicular to the cutting lines, was obtained on this metal matrix composite material.

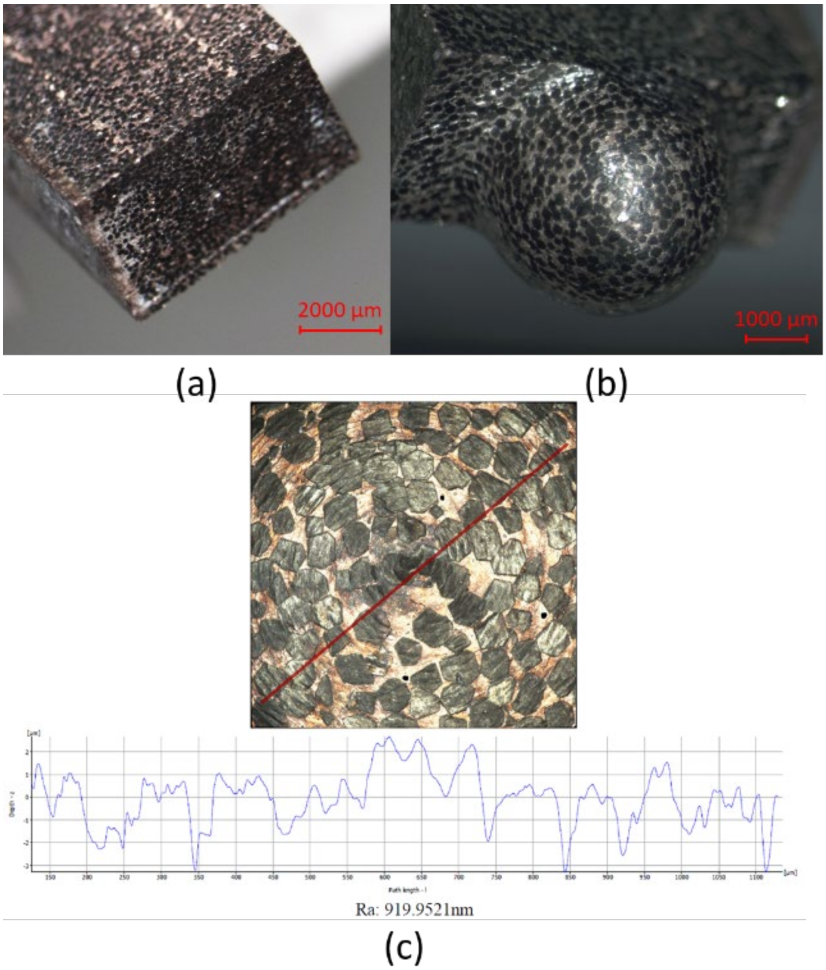


Fig. 7. Copper-diamond composite dome post LMJ tangential turning process (a) Sample before the turning process. (b) Sample post turning process. (c) Ra measurement.

3.2. Faceting roughing followed by tangential ablation finishing

Fig 8 shows an Aluminum tip, with a smallest diameter of 300 µm, produced by firstly approaching the final shape by cutting 4 facets and then performing a tangential ablation finishing step.

The final surface roughness measured perpendicular to the ablation layers reached Ra = 1µm. Depending on the feed per revolution and the surface speed of the turning process, different patterns arise on the sample surface. This sample was cut with a low feed per revolution resulting in high dimensional accuracy but causing vertical striations of the surface.

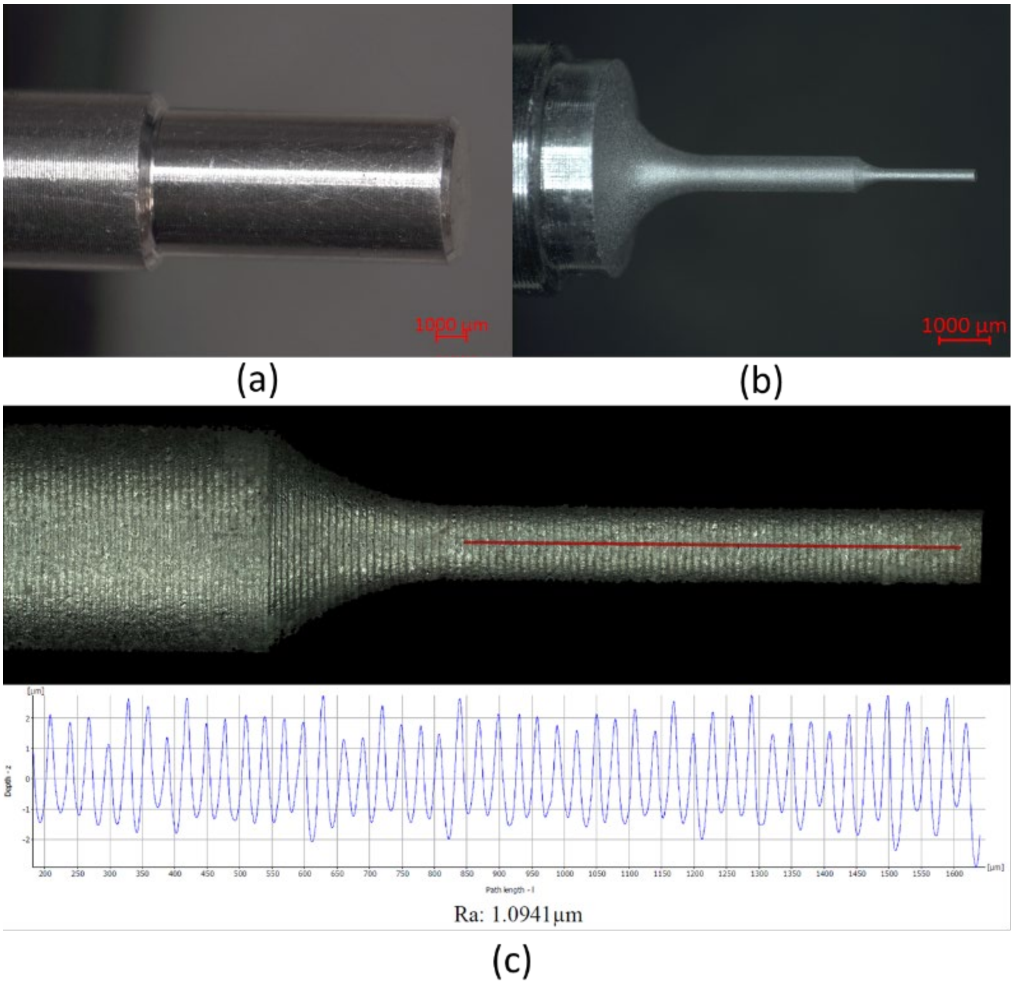
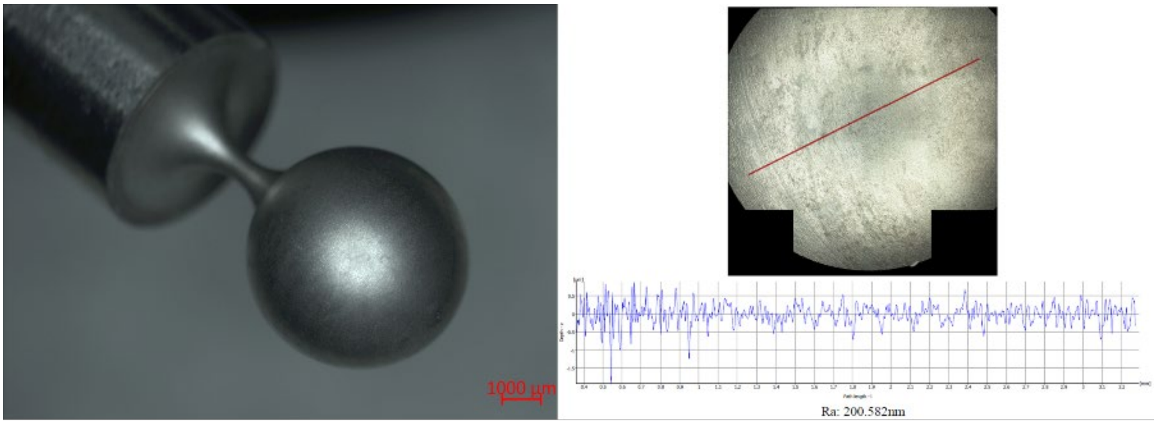


Fig. 8. Aluminum 300um diameter tip post LMJ faceting and tangential ablation finishing. (a) Sample before the turning process. (b) Sample post turning process. (c) Ra measurement.

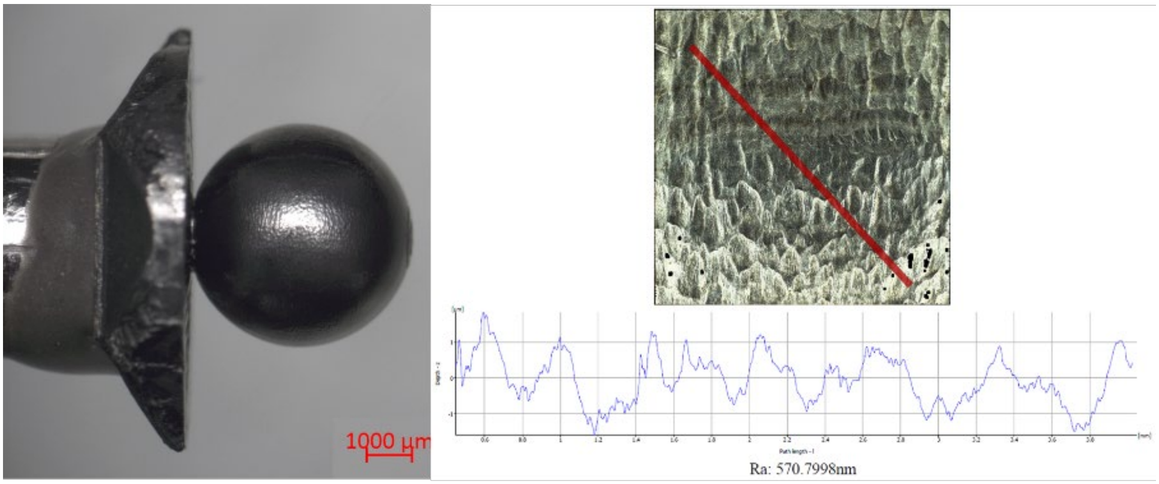
3.3. Fine faceting strategy

Fig 9 and 10 respectively show a steel and lab-grown diamond sphere produced by faceting the sample with a faceting angle of 1°. This small faceting angle allowed to reach Ra values as low as 0.2µm on the steel sphere and 0.6µm on the diamond.



(a) (b)

Fig. 9. Steel sphere post LMJ faceting process (a) Macroscopic picture. (b) Ra measurement.



(a) (b)

Fig. 10. Diamond sphere post LMJ faceting process (a) Macroscopic picture. (b) Ra measurement.

4. Conclusion

High-end turning processes benefit from the laser microjet versatile capabilities through several new strategies. LMJ can be used as a conventional turning tool machining the sample with normal incidence to maximize the MRR or tangential incidence to optimize the workpiece shape. In contrast to conventional turning and other energy beams, LMJ can be used to perform a faceting process. The faceting process enables a highly efficient roughing process as the large cut-outs removed during the process do not need to be ablated. If small faceting angle are selected, the faceting can also be used as an alternative finishing strategy leading to Ra values as low as 0.2µm. As these complex strategies have been demonstrated on diverse samples, it shines as a promising tool for efficient roughing and precise finishing on many shapes and materials.

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