RECENT ADVANCES IN PRECISION MACHINING OF SENSITIVE MATERIALS WITH THE LASER MICROJET®

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Abstract

The use of laser micromachining is becoming more popular nowadays, due to its versatility and flexibility. Recently lasers with very short pulse duration (sub-ns) or very short wavelengths (deep UV) are being employed, to further improve the micromachining quality (to reduce HAZ), compared to the results obtained previously with conventional lasers. These new lasers, however, have the well known disadvantage of low ablation rates and high running costs and, still suffer from the side effects of contamination, limited ablation depth and beam divergence. The Synova Laser MicroJet®, using a water jet-guided laser, has established itself as the alternative technology, for carrying out the processing of a wide range of industrial materials including those, that otherwise yield poor results or prove uneconomical, when conventional techniques are applied. To demonstrate the superior cutting quality, speed and economics of the Laser MicroJet® technology, extensive application developments have been carried out with the water jet-guided laser system for numerous international customers. Applications for the semiconductor industry included precision drilling of silicon wafer, cutting mould compound, cutting delicate optical elements from silicon wafer and cutting, grinding and chamfering of silicon wafer. Precision cutting of brass watch hands for the watch making industry has also been carried out. Applications have also been developed in cutting Nitinol for medicinal stents and cutting stainless steel tubing for use in endoscopy. For the machine tool industry cutting of up to 8mm thick PCD/WC or CBN/WC materials has been successfully demonstrated. All of these investigations have validated the claims made for the Laser MicroJet® concerning its very high quality of cut, high speed, accuracy and versatility. They have also demonstrated that the issues of heat damage, contamination and deposition, all of which are problems associated with any alternative laser manufacturing method, are completely resolved.

Keywords: Micro & Nano Technologies, water jet-guided laser, precision micromachining

1 Introduction

The initial discovery of guiding light in a column of water, dates back to the work of two researchers in Geneva, Switzerland over 160 years ago [1]. Since then, the basic principle has found various applications, notably in broadband fibre optic communications and non-invasive medical examinations. In 1997 the concept was successfully applied to the guidance of high power pulsed laser beams for use in the micromachining industry.

The purpose of this paper is to bring to the attention of the listeners some of the distinct processing advantages now being made possible using the Laser MicroJet® technology, the theory for which has been extensively described in earlier papers [2, 3].

The principle advantages of the Laser MicroJet® are its cutting speed, ability to cut both thin items as well as penetrate deep into thick target materials, producing perfectly parallel kerf walls, with no heat affected zone (HAZ) damage, as the water jet provides a continuous cooling effect and leaves no back surface chipping of the material. The water jet also provides an effective medium for cleaning the kerf of ablated material whilst exerting minimal mechanical forces, and simultaneously provides a protective film to prevent any deposition on the work piece surfaces.

This unique ability of the Laser MicroJet® (LMJ) water jet-guided laser to penetrate deep into the target material is based on the physical property of the kerf width being a few microns wider than the water jet itself, as depicted in Fig. 1. This leaves an air gap surrounding the jet, allowing for a loss-less guidance of the laser beam to the bottom of the kerf.

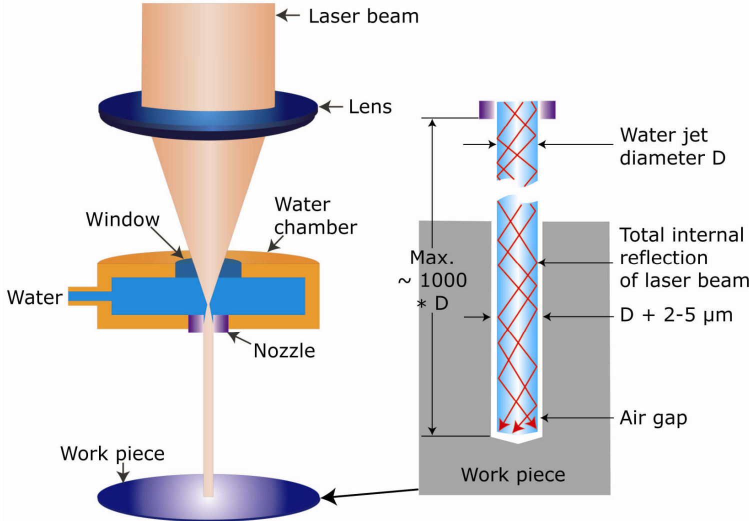

Fig. 1: Illustration of the water jet-guided laser principle and material penetration

This extraordinary effect means that cutting thick materials is perfectly possible, whilst maintaining the already added LMJ advantage of completely parallel kerfs. The maximum cutting depth is only limited by the size of the jet nozzle (D), which in turn determines the point at which break-up of the jet starts to occur (~1000 * D).

The examples given in the following sections detail some of the applications and materials, which are now being regularly processed in industry, or are the results of detailed application testing on behalf of external clients.

2 Semiconductor Applications

2.1 Silicon wafer drilling

An example of the capability of the Laser MicroJet® is the drilling of 100µm thick silicon wafer. Using the LMJ, this wafer can be drilled with excellent results, as is documented in Fig. 2. For this operation, a pulsed 532nm Q-switched laser was used. The nozzle diameter was 40µm and the water pressure 300bar. The 100µm holes were cut at a rate of 0.5s/hole.

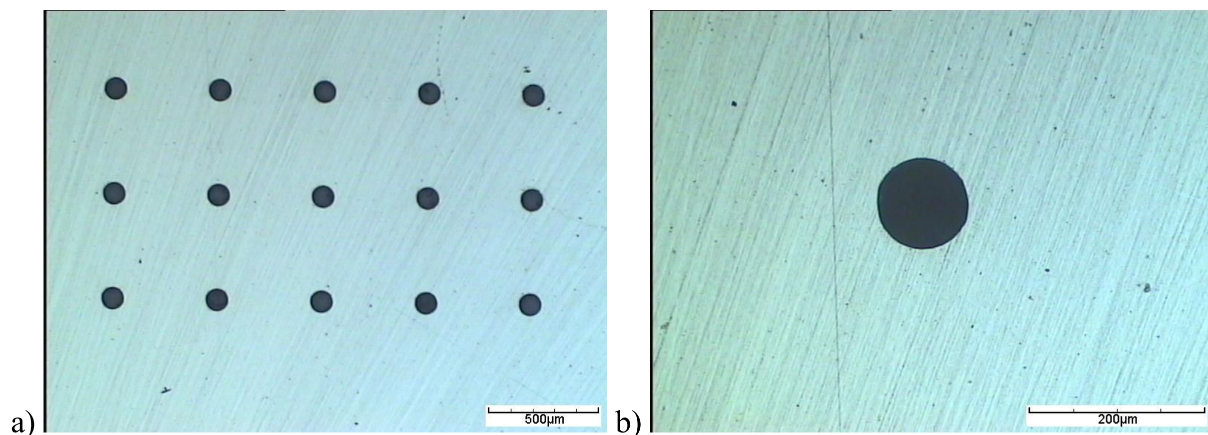

Fig. 2: Image of a) 100µm hole matrix front side view and b) enlarged view of one hole

2.2 Cutting thick silicon wafer

A second example of the capability of the LMJ, is the cutting of Ø100mm 1770µm thick silicon wafer. For a conventional dry laser the material thickness limit is ~200µm, due to divergence of the beam which, would with thick material such as this, result in angular kerf walls and a corresponding poor cut quality. Using the LMJ, thick silicon wafer can be processed with excellent results as is documented in Fig. 3. For this operation, a pulsed 532nm Q-switched laser, operating at 22kHz pulse repetition rate, with an average power of 31W, with the final through cuts made at 35kHz, 33W. The nozzle diameter used was 50µm and the water pressure 200bar. The cuts were made in 24 passes at 120mm/s for the initial cuts and 4 passes at 100mm/s for the finishing cuts. This gives a 257mm/min overall speed for the cutting operation. The ripple in the wall face in Fig. 3 amounts to <2µm.

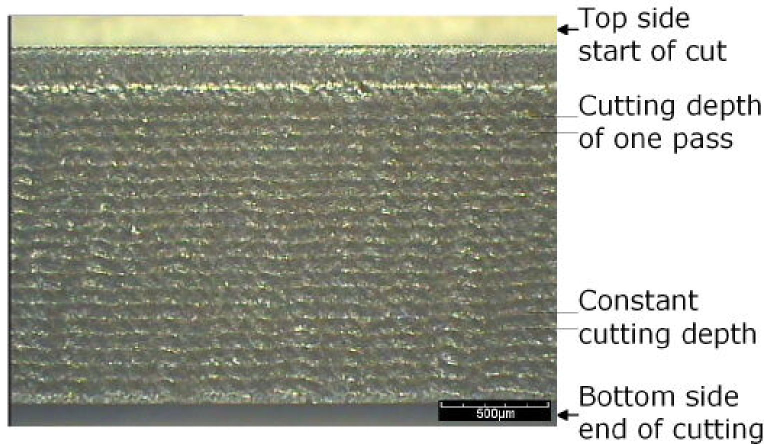

Fig. 3: Image of sidewall of 1770µm thick wafer, the cutting passes are clearly visible

2.3 Cutting optical elements from silicon wafer

A third example is the cutting of long “comb” like shaped structures from Ø300mm, 250µm thick silicon wafer, as shown in Fig. 4 a). The cutting consisted of 40*400µm wide and 125mm long “fingers”. The material was cut using a pulsed 532nm Q-switched laser, operating at 40kHz, with an average power of 32W. The nozzle diameter used was 50µm and the water pressure 150bar. Each cut was made in 4 passes at 100mm/s.

The quality of the cutting is shown in Fig. 4 b), which shows the “comb finger” tips after separation.

The resulting items, which form part of an x-ray optical system, exhibited perfectly clean cuts, with no burrs, micro cracking, deposition or thermal deformation, and exhibited high fracture strength.

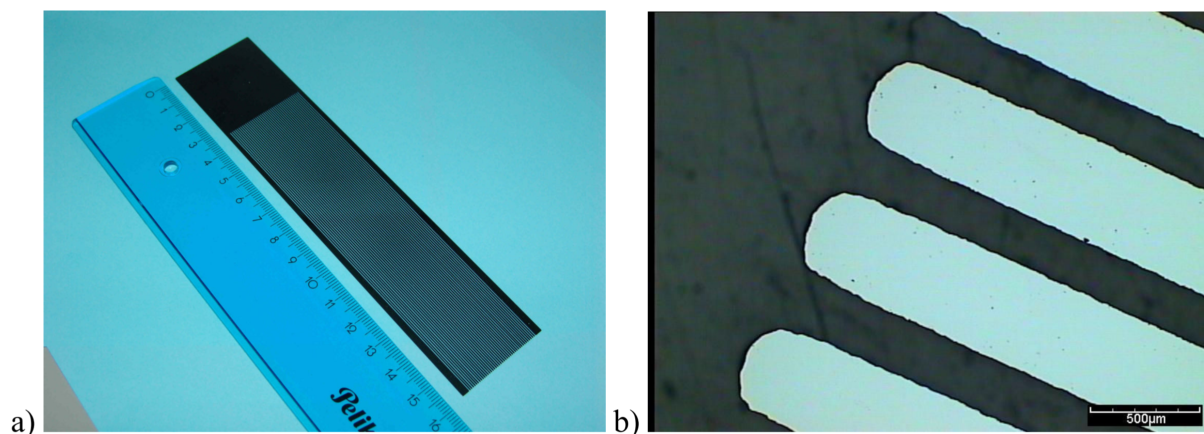

Fig. 4: a) "Comb" structure cut from 250µm silicon wafer and b) enlarged view of tips after separation

2.4 Silicon wafer edge chamfering

A final example of the capabilities is the cutting and grinding of 45° chamfered edges on Ø300mm polished 700µm thick silicon wafer.

The following steps were carried out using a pulsed 532nm laser, operating at 15kHz, with an average power rating of between 7 and 10W. The LMJ was fitted with a 50µm nozzle and the water pressure was 180bar.

The first step is the preparation of the wafer to have sharp edges, by implementing a straight cut in three passes. The grinding operation to produce top and back surface 45°chamfered edges was then carried out as depicted in the following Fig. 5.

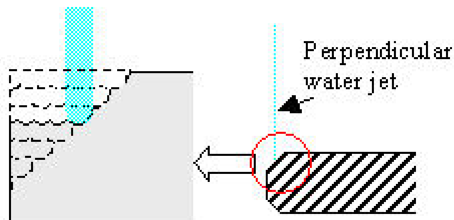

Fig. 5: Chamfering in multiple passes

Each layer is removed using a number of adjacent cutting scans with a 20µm overlap, starting at the outside and moving inwards. With optimised parameters, the required different chamfers widths were produced on both sides as listed in Tab. 1.

Tab. 1: Processing times for different chamfer widths

Nr. passes/side	Chamfer width [µm]	Chamfer height [µm]	Total Process time [s]
15	130-135	135	189
66	340	380	829
36	250-275	260	452

The results of the processing are shown in the following Fig. 6 a), which shows the side wall face and Fig. 6 b), which shows the chamfer face. Unlike with conventional grinding techniques, there was no micro cracking at the wafer edges.

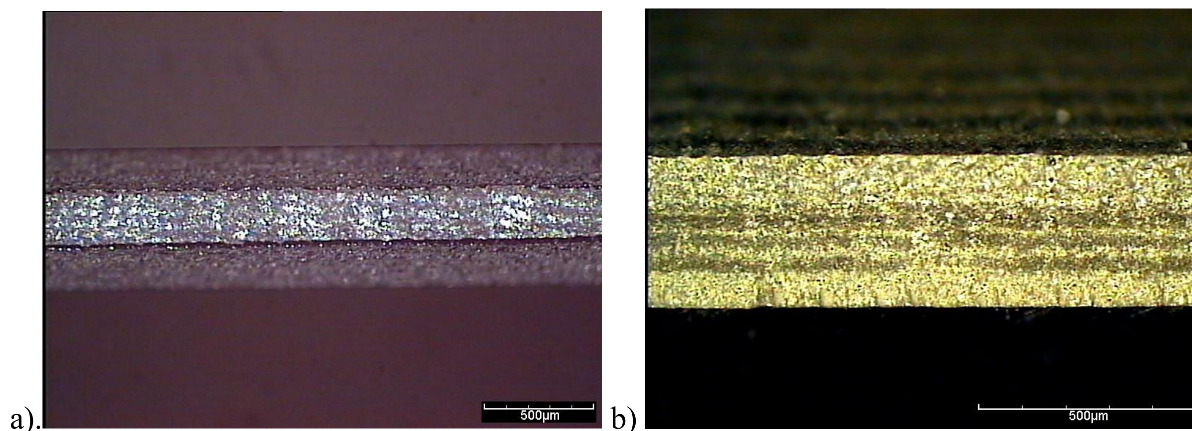

Fig. 6: Microscopic image a) of typical wall cut with chamfers and b) chamfer surface

The above four examples demonstrate capabilities of the LMJ, which no conventional dry laser can achieve. In addition, there are the added advantages of little or no post processing requirements, as the ablated material is flushed away by the water jet and the protective water film which forms on the work piece surfaces, stops any deposition occurring on the material.

3 Watch Applications

The hands used in today's watch mechanisms, either the pure mechanical or battery driven varieties, place demanding requirements on the manufacturers, especially for items destined for the luxury goods market. Cutting such fine mechanical parts, which are normally made from either brass or steel, with conventional dry lasers does not produce good results, due to the resulting deformation effects from heating, burrs and deposition of ablated material. These in turn require additional processing steps, before the part can finally be used.

Traditional production methods require the manufacture of special tooling for each part, which is costly, requires an appreciable lead time and is inflexible. In comparison, the Laser MicroJet® offers the manufacturer a highly flexible programmable solution for cutting one-off unique design items, through to mass production of parts for the consumer market.

Using the Laser MicroJet® as a cutting tool for watch hands from 200µm brass has been demonstrated, with excellent results. For the tests, an LSS800 stencil cutting machine was employed, using an Nd:YAG 532nm pulsed laser, operating at 18kHz and average power of 30W. The LMJ was equipped with a 40µm nozzle, operating with a water pressure of 280bar.

One of the main goals was to demonstrate a high cutting speed and achieve a time of <8 seconds/hand in continuous operation. The image Fig. 7 shows the brass sheet after the separation of the watch hands following a short test run.

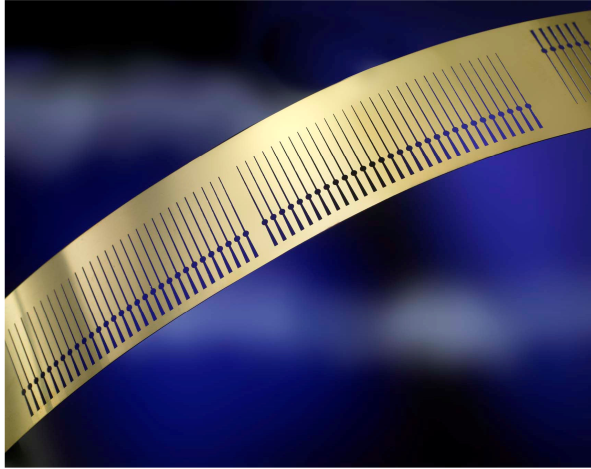

Fig. 7: Result of continuous cutting of watch hands

The following Fig. 8 show enlarged views of the separated watch hand surfaces directly after cutting.

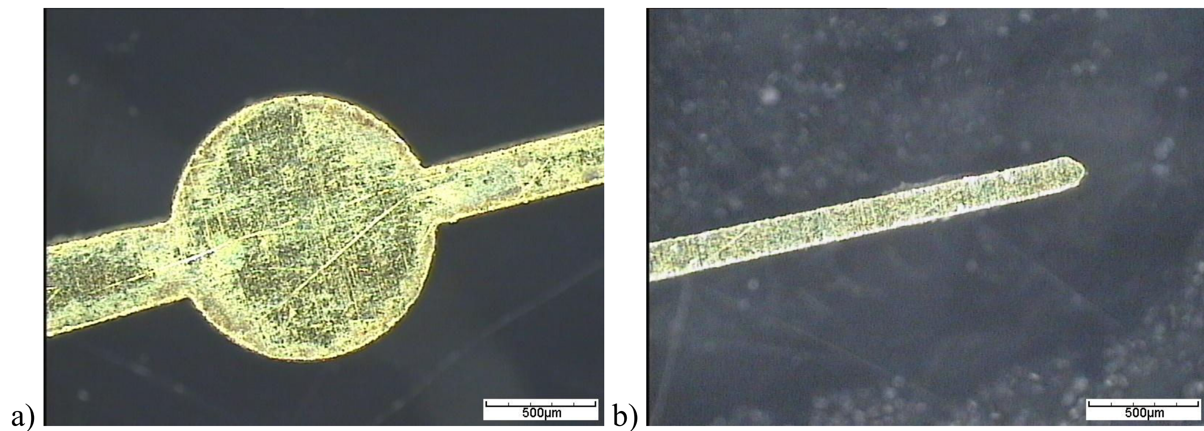

Fig. 8: Microscopic image of a) front side of brass watch hand and b) back surface of tip

Note that the discoloration of the material in the above images is <u>not</u> due to the LMJ cutting process.

4 Medical Applications

4.1 Stent cutting

The Laser MicroJet® has also proved itself in the manufacturing of medical devices, especially stents. These devices, which are essential for today's increasing use of non-invasive surgery practices, are used extensively for counteracting localised constrictions in bodily organs, such as arteries which have been cleared after angioplasty. The stent is installed on a balloon catheter in a collapsed state, moved to the affected area and then

expanded by inflating the balloon, the stent then locks into place in the artery, forcing it to remain open.

Since the stent will remain inside the human body, and is crucial to the patient's long-term health, the finish is paramount, requiring a high level of quality control during fabrication, i.e., clean smooth surfaces with no attached dross or burrs.

The devices require the cutting out of intricate patterns in the metal sheet or tube to obtain struts, the shape of which together with the type of material employed, determine it's expansion characteristics. The main materials used are flat or tubular stainless steel, titanium, or Nitinol (NiTi) of varying thickness or diameter. Of these three materials, 316L stainless steel, which is non-ferrous, is the most widely used. For flat sheets, which are later bent to form a tube and welded; the material thickness can vary between 100 and 200µm. For tubular stents, the diameters typically vary from 1 to 5mm and the tube wall thickness from 30 to 600µm.

Conventional cutting using an Nd:YAG laser, characteristically leaves an oxide layer on the surface of the stent, and remelt on the sides of the struts due to diffusion of the laser beam. These unwanted artefacts must then be removed, typically using a closely controlled micro blasting process, to avoid weakening the strut joints, which could subsequently lead to premature device failure. Besides these additional processing steps, other factors such as cutting speed and the degree of automation required, all contribute to a limited throughput in stent production.

In comparison, the LMJ provides excellent and fast cutting quality (parallelism and smoothness) and especially no thermal damage. Stent materials exhibit excellent absorption properties at infrared (IR) and so efficient machining with lasers operating at this wavelength is possible. Using a pulsed diode pumped 1064nm laser operating at 1.5kHz, with 23W average power, and a cutting speed of 9mm/s, a clean, remelt-free cut is achieved and the continuous water jet immediately cools the material.

The results are a very narrow burr-free cut, with parallel kerfs, little or no thermal penetration and no oxidation as can be seen in Fig. 9. As no remelt is created during the cutting, micro blasting can be significantly reduced or even eliminated. The LMJ process increases the quality of the manufactured item and removes the danger of stent failure due to weakened struts, eliminating possible future legal liability issues.

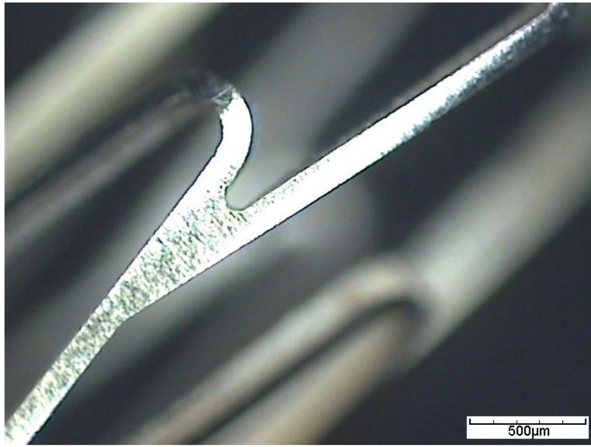

Fig. 9: Microscopic image of stent made from 200µm Nitinol directly after LMJ cutting

4.2 Cutting tubing for endoscopy

A further example of medical devices, which can be cut using the LMJ, requiring exceptionally high quality, is for stainless steel tubing used in endoscopy. When cut using conventional dry lasers, the devices require considerable post processing to produce an acceptable finished product. The same devices when cut with the LMJ produce an almost perfect finished product, requiring only a minimum of post process cleaning.

The article shown in Fig. 10 a) and b), was cut completely through in a single operation from Ø5.2mm 316L stainless steel tubing, having a wall thickness of 350µm, with a pulsed 532nm laser, operating at 25kHz and an average power of 60W. The jet nozzle diameter was 50µm, water pressure 400bar and the cutting speed 25mm/s. The processing time for the complete part was ~140 seconds.

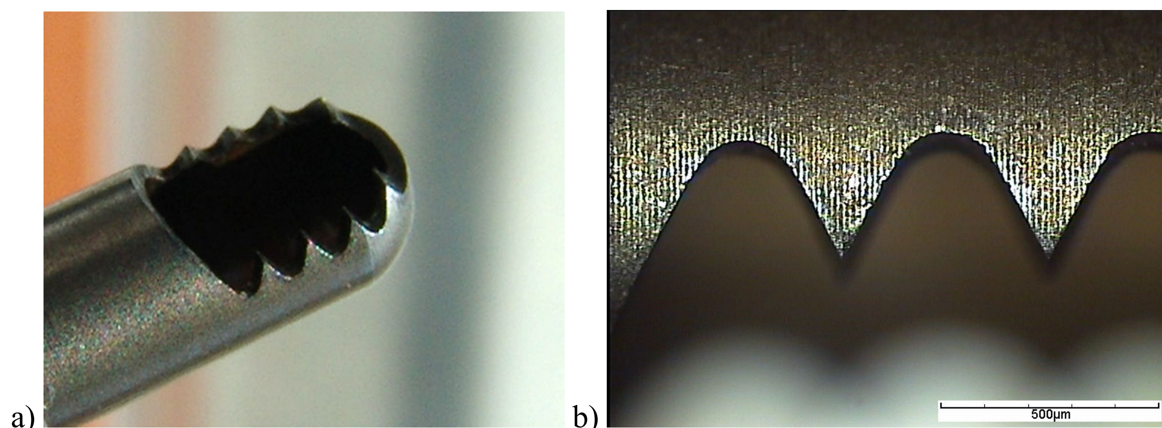

Fig. 10: Ø5.2mm 316L stainless steel tube directly after LMJ cutting, a) view of the finished part and b) microscopic image of front surface

5 Tooling Applications

The machine tool industry is being faced more and more with producing tooling for manufacturing parts made from hard or difficult to process materials. The tools themselves have to be made from hard materials to ensure an economical lifetime for the part. These tools are now often made from pure Diamond (C) also in it's PolyCrystalline Diamond (PCD) form, cubic Boron Nitride (cBN), or Silicon Nitride (SiN), only now being overtaken by newly discovered and still exotic materials such as Aggregated Diamond NanoRods (ADNRs) and Ultrahard Fullerite (C_{60}).

The presently accepted machining methods involve the use of lasers, grinding and Electrical Discharge Machining (EDM). All of these methods, however, have their own distinct disadvantages. Dry cut lasers cannot be used to cut thick materials, without leaving behind a heat affected zone (HAZ) around the cut area, thereby lowering the quality and usefulness of the finished article. Grinding is an accepted method, but is costly in terms of grinding media, also leaves a damaged area, and is not suited to complex shapes. EDM is a proven method, but will only work with electrically conductive materials, is slow and leaves an oxidised surface on the cut edges.

The Laser MicroJet® offers a tool where the laser beam can cut into, cut through and even cut complex 2-D shapes in ferrous or non-ferrous materials, producing clean perfectly parallel kerf walls, with no burrs, no contaminants, no re-deposition, and is not reliant on electrical conductivity of the work piece. For cutting these hard materials, machine processing tables of 300*300mm are available, with axis speeds of up to 1000mm/s, absolute precision of ±3µm and repeatability of ±1µm.

For cutting complex layered tooling made from CBN/WC material, two recent applications demonstrating the use of the LMJ are described below.

A "Christmas tree" shape was cut from a 5mm WC disk with a 5mm thick CBN insert, using a pulsed dual cavity Q-switched 532nm laser, operating at 8kHz, with an average power of 140W. An 80µm nozzle used was, with a water pressure of 400bar. The cutting was made at 10mm/s with 220 passes, giving an overall speed of 380s/insert.

A view of the top surface of the tool insert, showing the tip after cutting, can be seen in Fig. 11.

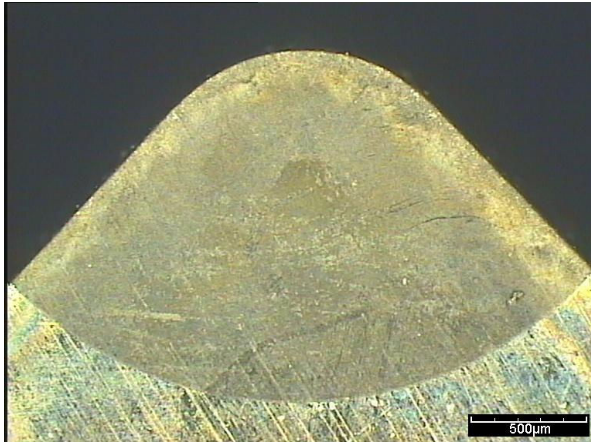

Fig. 11: Microscopic view of front side showing the CBN insert

The second example was to make a chamfered cut through a Ø13.4mm cylinder composed of a 1.0 – 1.5mm thick CBN layer on a 6.5 – 7mm WC backing. Cutting parameters were as for the previous example. The cutting speed was 20mm/s requiring 700 passes, giving an overall speed of 600s/insert.

The following Fig. 12 depicts the direction of the cut made through the CBN layer into the WC backing material.

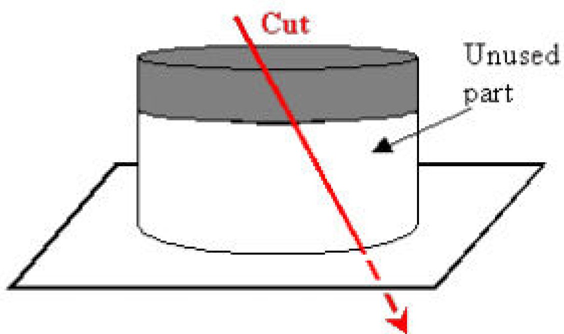

Fig. 12: Sketch showing the cutting requirements

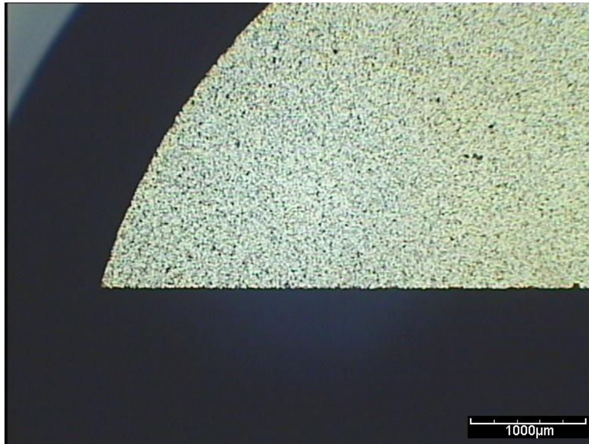

Fig. 13: Microscopic image of topside of CBN material after cutting

6 Conclusions

As mentioned at the beginning of this paper, this series of results is presented to give insight into the potential capabilities of the Laser MicroJet®. The results show that the LMJ is an appropriate machining technology for many high precision cutting applications. The cuts are clean, reliable, accurate, and show negligible or no heat damage. In particular, the cutting of complicated shapes such as stents provides excellent results, achieving a consistent pattern transfer. The wide range of applications and materials suitable for processing with the LMJ, make this tool a worthy challenger to any other form of micromachining.

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