Femtosecond Laser Micromachining: Current Status and Applications

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ABSTRACT

Femtosecond lasers currently show much promise as potential sources of choice in a number of laser micromachining applications, including biomedicine, photonics and semiconductors. The status of micromachining with femtosecond pulses is reviewed for a variety of materials and a comparison made with other solid-state lasers. An outlook for developments in this area is presented.

INTRODUCTION

The use of ultrashort laser pulses have been shown to be an attractive option for the high quality micromachining of many materials and their ability for minimal damage and precise processing has been thoroughly researched for many years[1-4]. The increasing worldwide interest in femtosecond laser micromachining and the potential new markets being investigated have prompted the laser manufacturers to develop more powerful, simpler, rugged and more competitive laser systems and this, in turn, has encouraged further work.

The issue of future industrial applications of femtosecond lasers is still a hot topic for debate and it is not currently clear which application, if any, will emerge as the dominant user of femtosecond technology in an industrial context. This debate is further clouded, however, by the continuous and rapid developments in other solid-state lasers that continue to extend the frontiers of high quality laser micromachining using nanosecond pulses.

This article presents femtosecond laser micromachining of different materials with a view to showing the possibilities present in certain areas. Other competitive techniques are also highlighted where they can offer significant benefits or alternatives to femtosecond micromachining.

FEMTOSECOND LASER MICROMACHINING

A qualitative study has been performed on the femtosecond laser micromachining of a variety of materials. Using either a Spectra Physics "Hurricane" laser or a Thales "Bright" laser[5], both of which have similar output specifications (λ_0~800nm, $\Delta\tau$~110fs, E~1mJ/pulse, Rep Rate~3-5kHz, M^2~1.2), various structures have been machined into the samples and the overall quality assessed.

General qualitative results are presented in the following sections which show the possibilities of ultrashort pulse machining. In some cases, comparative nanosecond laser results are also presented to show an alternative technique with similar results.

Metals

The micromachining of bulk metals was historically a difficult task using nanosecond (or longer) pulse lasers due to issues to do with melting effects around the machined site, recast material and general edge quality of the microstructure. The fine control which was required for precision microstructures could not be obtained with such lasers. Recently, femtosecond lasers have overcome these problems and high quality micromachining is now possible[6] in a range of bulk metals, as shown in figure 1.

The other recent development which has affected the area of metal micromachining is the development of high repetition rate solid-state lasers, particularly neodymium vanadate (Nd:YVO_4) lasers. The relatively short pulse duration of these lasers (typically a few nanoseconds to a few tens of nanoseconds) and repetition rates of a few tens of kilohertz have enabled sufficiently robust processes to be developed such that extremely high quality micromachining has also been demonstrated using these nanosecond pulse systems. Figure 2 shows an example of high precision micromachining using a 355nm Nd:vanadate laser operating at 10kHz and with an average power of 6W and a pulse duration of 38ns.

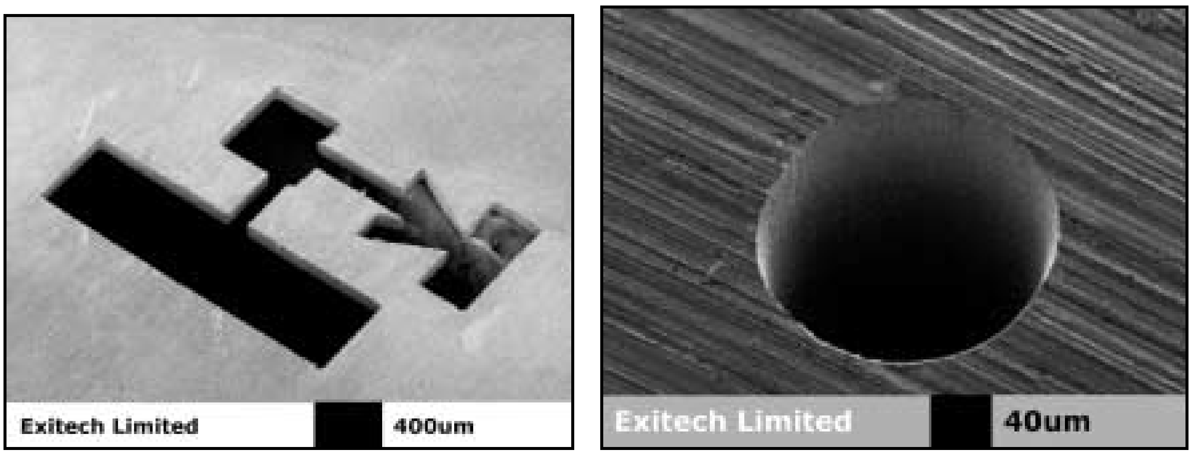


Figure 1. Femtosecond laser micromachining of aluminium (left) and steel (right).

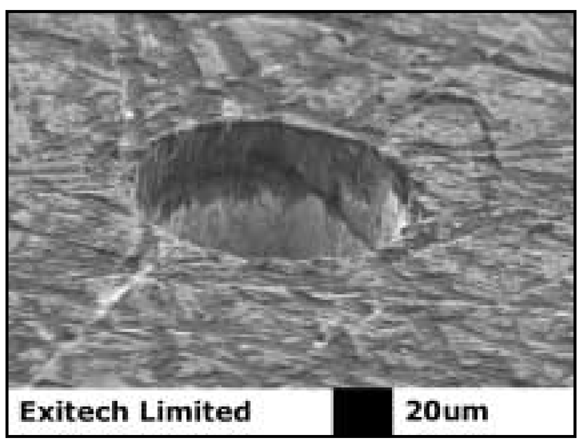


Figure 2. 100μm diameter hole drilled in stainless steel using a 355nm nanosecond pulse Nd:vanadate laser.

It can be seen from figure 2 that even with metals such as stainless steel, which are relatively difficult to laser machine with good quality, comparatively good results can be obtained using nanosecond pulse lasers if proper process optimisation is undertaken.

Glass

The use of glass-based microstructures in disciplines such as biomedicine, biochemistry, lab-on-chip devices, sensors and MEMS devices has led to increasing attention being paid to glass micromachining. In almost all cases, it is desirable to avoid damage and micro-cracks around the laser machined site and femtosecond lasers have proven to be excellent sources for such precise machining work. Figure 3 shows two examples of borosilicate glasses machined using a femtosecond laser.

Diamond

Synthetic CVD diamond has received a lot of attention as an attractive material for different applications such as for use in IR optical applications, detectors, sensors and thermal management systems. The diverse range of applications results from the unrivalled set of mechanical, thermal, electrical and optical properties that diamond exhibits. However, one of the drawbacks which results from the inertness and mechanical hardness of diamond is that is relatively difficult to machine or etch conventionally. Lasers can overcome these difficulties and various nano-millisecond pulse lasers (e.g. IR Nd:YAG lasers) have been used for a number of years for the cutting and dicing of diamonds.

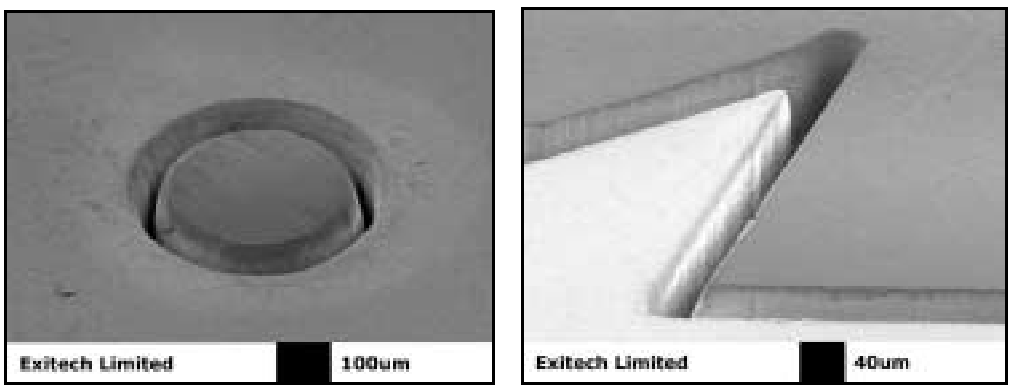
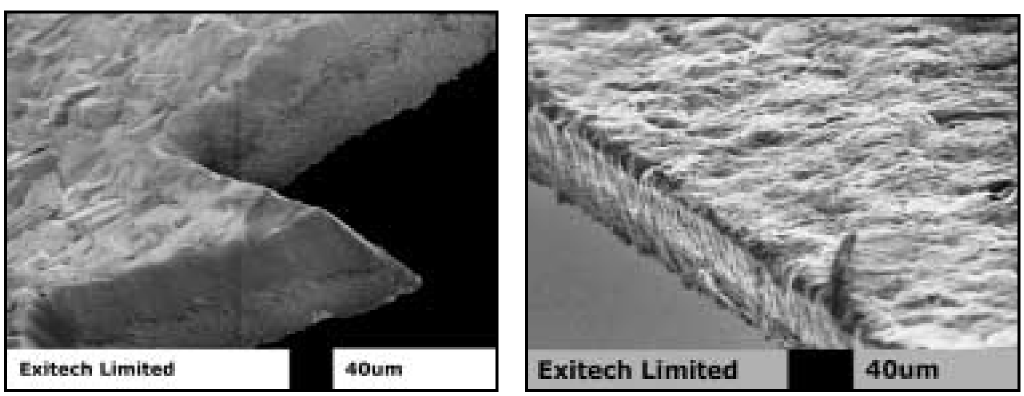


Figure 3. Glass samples micromachined using a femtosecond laser.



(a) (b)

Figure 4. (a) Cutting of a CVD diamond wafer using a femtosecond laser, (b) sample of CVD diamond where the surface ha been smoothed using a femtosecond laser and the edge has been cut using a nanosecond pulse 355nm Nd:YVO_4 laser.

As diamond devices have matured, however, a number of more stringent criteria have appeared which have meant that the existing 'long' pulse lasers can no longer meet the necessary quality. In particular, the use of diamond substrates for detector and sensor devices requires the addition of electrical circuitry on the surface of the as-grown diamond. To achieve proper deposition and contacts on the surface, the metal electrodes need a smoother surface than is present with the as-grown substrate.

Laser smoothing can be used to remove the facets from the surface to leave a flatter surface. UV excimer laser smoothing has been demonstrated and results in a very good quality, 'smooth' surface. The only drawback with excimer laser smoothing is that is also results in graphitisation of the surface, which is a detrimental effect when considering electrical connections. The use of femtosecond laser smoothing does not graphitise the surface in any appreciable manner and electrical tests conducted on femtosecond laser smoothed diamond have confirmed this. Figure 4 (a) shows a fs-laser cut piece of diamond and fs-laser smoothing is shown in figure 4(b).

Fluoropolymers

The recent development of miniature lab-on-a-chip system technologies have re-ignited interest in the laser machining of materials such as PTFE and other fluoropolymers, since they offer resistance to chemical attack and therefore allow the integration of a wide range of chemical reactions in small devices. These materials are traditionally very difficult to machine with nanosecond pulse lasers, especially if small feature sizes and high quality are required.

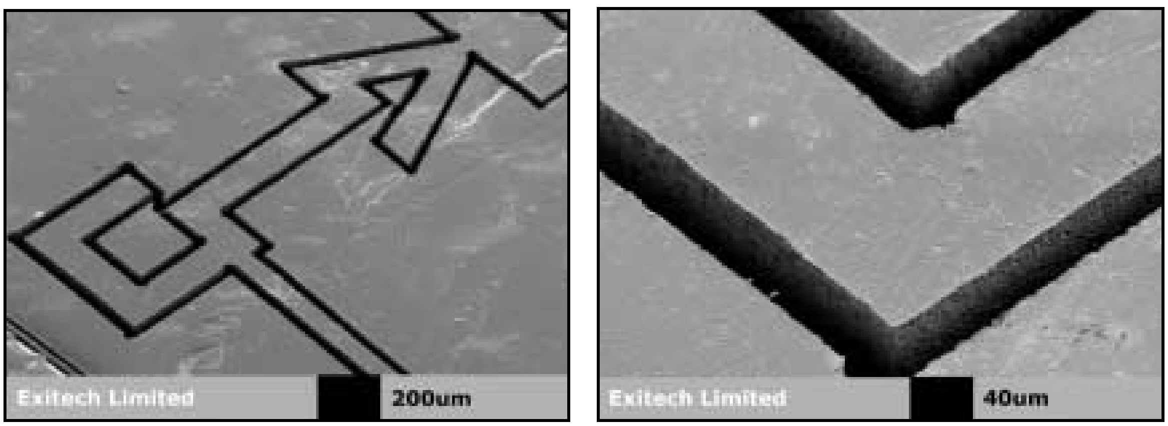


Figure 5. Samples of FEP micromachined using a femtosecond laser.

Femtosecond pulse laser micromachining has been shown to be excellent at machining fluoro-compounds and results from FEP are shown in figure 5. Such high precision and damage-free results are almost impossible to obtain with machining using longer pulse lasers with the possible exception of 157nm fluorine lasers.

PMMA

PMMA has been used for many years as a photoresist, particularly in LIGA applications. The laser machining requirements for PMMA have emerged recently mainly due to LASER-LIGA work and its use for the production of micro-optical components, where PMMA's blend of mechanical, thermal, chemical and optical properties make it an attractive material. Figure 6 shows a micro-trench machined into PMMA using a femtosecond laser.

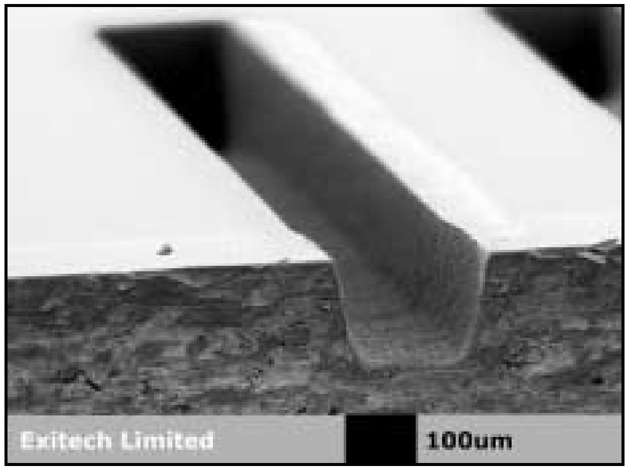


Figure 6. Trench machined into PMMA using a femtosecond laser.

Silica

Fused silica has emerged as a major material of interest for the telecommunications industry since it serves as an excellent host material for optical waveguides in the near infrared. It is also used as an insulator material or barrier layer, often in combination with silicon in other photonics devices. Due mainly to its absorption properties, it is usually not very easy to machine silica directly with ‘conventional’ nanosecond pulse lasers. Femtosecond lasers have been used to machine silica with excellent results, however, and both fibre samples and bulk materials have given excellent results. Figure 7 shows samples of bulk silica which have been machined using a femtosecond laser. The samples have not been cleaned or processed further after laser machining and the excellent quality and lack of damage and debris is clearly evident.

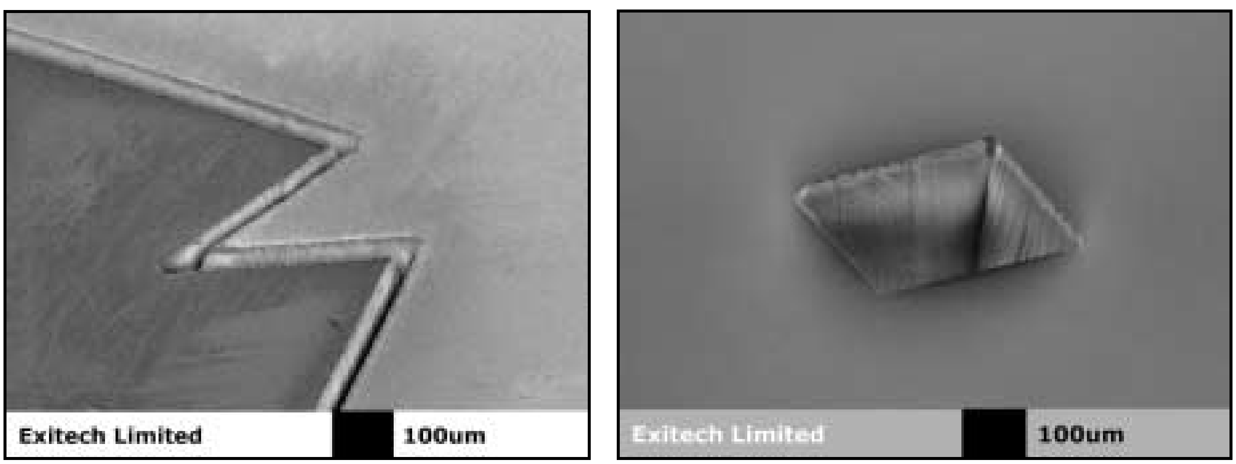


Figure 7. Samples of silica micromachined using a femtosecond laser.

Another application of femtosecond laser micromachining that has emerged recently is the direct writing of optical waveguides[7] inside glasses and silica using femtosecond laser pulses. This technique offers a simpler and more flexible technique for the production of waveguides than the conventional methods and is set to be investigated and exploited more in the future.

Although bulk micromachining of silica is also possible with high quality results using 157nm lasers, as shown in figure 8, the waveguide writing is a unique application where only femtosecond lasers have so far proved to be successful. As such, this may prove to be one of the key driving technologies which push femtosecond lasers forward.

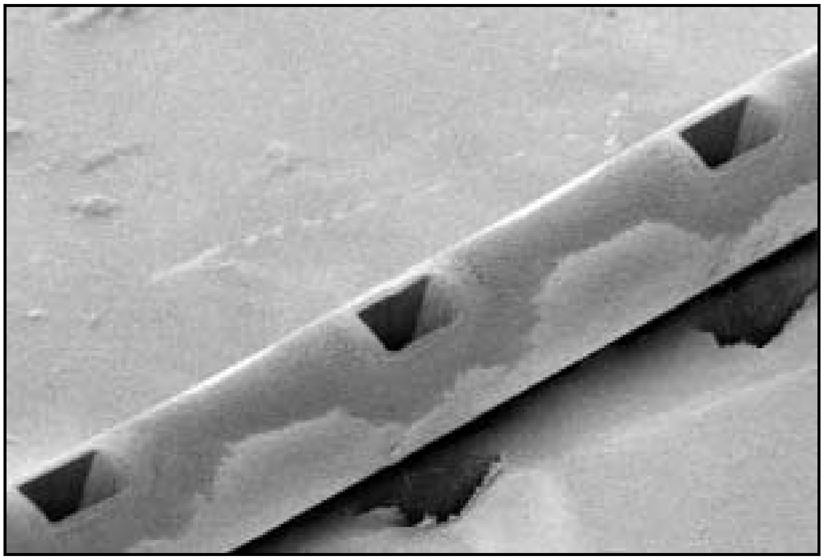


Figure 8. Direct 157nm laser micromachining of facets in silica cladding of an optical fibre.

Optical Materials

Also of interest in telecommunications and photonics applications are optical materials such as lithium niobate, lithium tantalate, indium phosphide, GaAs and other similar semiconductor compounds. Such materials are used in products such as lasers, amplifiers, modulators and switches and commonly require structures and features of high quality. Although nanosecond lasers can be used for the micromachining of these materials, femtosecond pulse lasers do provide excellent results without causing damage to other features in close proximity to the machined site.

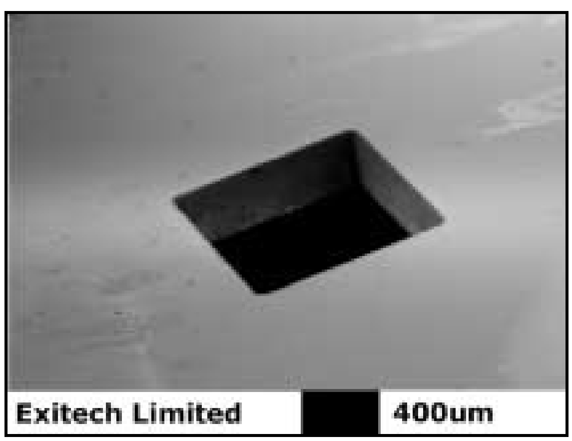


Figure 9. Sample of lithium tantalate machined with a femtosecond laser.

Figure 9 shows a wafer of lithium tantalate from which a small tile has been extracted using a femtosecond laser. The ability to perform highly selective micromachining is a distinct advantage of femtosecond lasers although other nanosecond sources (such as excimer lasers and harmonic neodymium-based lasers) can produce excellent results for a variety of tasks such as wafer cutting or the production of v-grooves. The use of femtosecond lasers may find particular importance in micromachining of populated photonics chips where adjacent structures need to be completely undamaged by the micromachining of features on the chip.

Masks

Photomasks used in semiconductor lithography usually contain certain defects which, depending on their size and position, may make the mask unusable. Since the masks are relatively expensive to manufacture, it is desirable, not least for economic reasons, to repair or remove the defects to make the mask fully usable again. The criteria for this defect removal include: (i) the underlying quartz should not be damaged, (ii) the chrome regions around the repair site should not degrade in quality or have debris on them, (iii) the transparent regions of the mask around the repair site should not suffer from re-deposited materials, (iv) the repair site should not be thermally affected and (v) the repair method should be able to remove the smallest dimensions on the mask. Femtosecond lasers can remove the chrome layers very cleanly without thermal effects and without affecting the surrounding or substrate layers and so have emerged as an advanced candidate for mask repair applications.

Figure 10. A chrome-on-quartz photomask where the chrome has been removed using a femtosecond laser.

Figure 10 shows 10μm wide tracks made in a 100nm thick chrome layer in a commercial photomask. Although this track width is an order of magnitude or more larger than the smallest features required to be removed from modern masks, it demonstrates the effectiveness of femtosecond pulses n the high quality removal of chrome layers for mask repair applications.

Ceramics

A variety of materials such as zirconia and aluminium carbide are used widely in the microelectronics sector and in other MEMS-type devices. Applications include the test devices for integrated circuits, substrates for sensors and detectors, micro-cavity structures inside biomedical or chemical diagnostics and transducers.

Figure 11 shows a high quality microcavity machined in zirconia using a femtosecond laser. As in the case of some of the other materials presented here, competitive nanosecond laser machining techniques exist but, as before, the lack of any thermal influence on the sample is often the crucial factor.

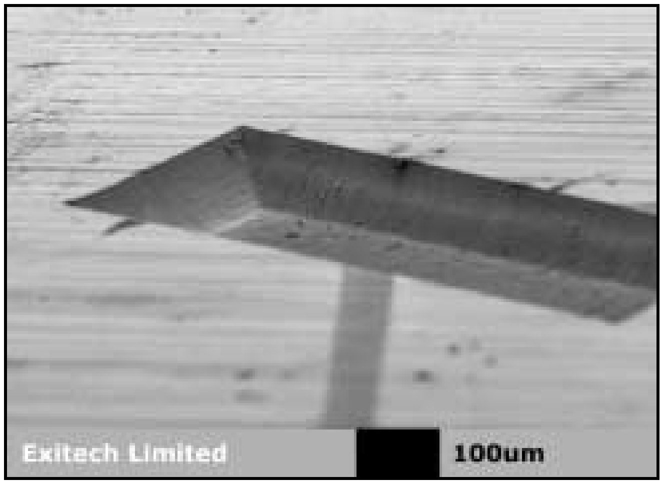


Figure 11. A microcavity machined into zirconia using a femtosecond laser.

Biodegradable Polymers

In biomedical developments, the use of biocompatible materials is receiving much attention since this opens the highly beneficial possibilities for future medical implants. One of the specific areas of development has been biodegradable stents. Stents are used as expandable devices which are used after arteries have been unblocked or cleared and their aim is to stop the collapse or closure of the arteries. Currently, stents are made of metals (which are mostly machined using nanosecond pulse neodymium lasers) but this means that further surgical procedures are needed to remove the implants after a certain time. If stable, high quality polymer stents were available, then these could be implanted and would not need to be removed as they would degrade naturally inside the artery over time.

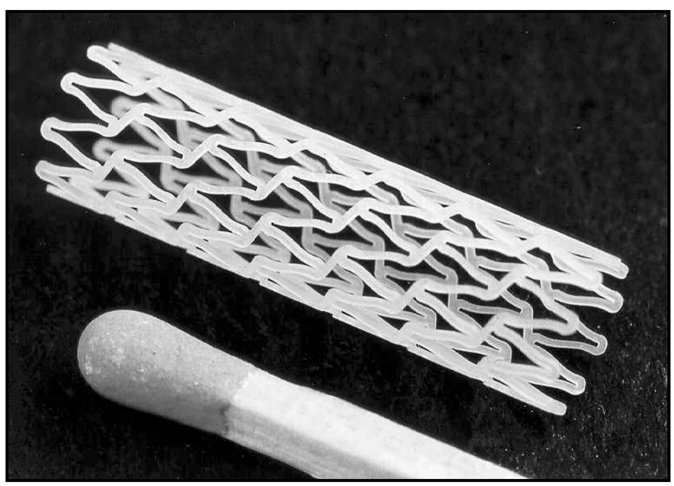


Figure 12. A medical stent micromachined from a biodegradable polymer using a femtosecond laser
(Courtesy of LZH/Cortronik)

Many of the candidate materials can be machined with neodymium or excimer lasers but they suffer too much degradation in their mechanical properties to be viable for implanting. Femtosecond lasers can not only produce the desired quality in the biopolymers but also do not affect their mechanical strength. Figure 12 shows a stent made from a biopolymer using a femtosecond laser. As in the case of photonics waveguides, this may become a ‘driver’ application as no other alternative machining method is available if biopolymers are to be manufactured.

EMERGING INDUSTRIAL APPLICATIONS

There are a number of emerging candidates for the application area which might drive femtosecond laser technology into mainstream, mass-market industrial use - the ‘killer application’, as it is often called. Some of the applications sectors include:

- Biomedical devices: use of femtosecond lasers for stent manufacture or eye surgery. This is thought to have huge benefits in terms of precision, damage to the surrounding area and patient recovery.

- Surface structuring: surface smoothing without imparting any thermal influence into the substrate or for the selective machining of multi-layer devices without affecting particular layers.

- Micro-optics: machining of micro-lenses or diffractive optical elements in optical materials with a high surface finish.

- Photonics devices: machining of optical waveguides in bulk glasses or silica for photonic lightwave circuits and other telecommunications devices.

- Micromachining: drilling of diesel injector nozzles or other thick metal machining. It should be noted, however, that this particular application has been touted for many years without advancing significantly and it may now be the case the nanosecond lasers may offer sufficient machining quality to be suitable for production of injector nozzles.

It is not clear which of the above applications, if any, will mature sufficiently in the future or whether other applications may emerge. There is no doubt that the range of applications being addressed with femtosecond lasers is increasing, although the prospect for industrial manufacturing is still uncertain.

SUMMARY & DISCUSSION

The excellent quality of micromachining which is possible with femtosecond lasers is beyond question in a very large range of materials. It has to be borne in mind, however, that substantially similar results are also achievable in many materials by using ‘conventional’ nanosecond pulse solid-state lasers and so it should not be assumed that femtosecond lasers are always the best option in all cases. It has been shown here that alternative laser sources can provide results which may be as good, if not better, than those obtainable with femtosecond lasers. There are a small number of application sectors, such as medicine and the production of optical waveguides, for example, where the unparalleled results achievable with femtosecond lasers may be the driver for the increased uptake of this technology and where the long-sought-after ‘industrial’ use of femtosecond lasers may mature.

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