Advantages of picosecond laser machining for cutting-edge technologies

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Abstract

The demand to reduce the size, weight and material cost of modern electronic devices results in a requirement for precision micromachining to aid product development. Examples include making smaller and more powerful smartphones with brighter displays, eliminating the requirement for post-process cleaning and machining the latest bio-absorbable medical stents. The pace of innovation in high-tech industries has led to ultrafast (picosecond) industrial lasers becoming an important tool for many applications and the high repetition rates now available help to meet industrial throughput levels. This is due to the unique operating regime (megawatts of peak power) enabling clean cutting and patterning of sensitive materials and thin films used in a number of novel devices and allows micromachining of wide bandgap, “difficult” materials such as glass.

Keywords: picosecond laser; ultraviolet; glass; micromaching; steel; fuel injection nozzles; bioabsorbable stents; medical; smart phones; displays

Nomenclature

| $E_p$ | Laser pulse energy |

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1. Introduction

The continuous reduction in electronic device size and weight is also decreasing the permissible dimensions and tolerances, which have raised demand for the high quality machining ultrafast lasers can produce. The short interaction time of picosecond laser pulses means that a given material can be removed before the material has time to react to the thermal/mechanical shock of the laser pulses Karnakis, 2010. As indicated in Fig. 1, very high quality features can be produced by keeping the laser fluence close to the laser ablation threshold. However, as the laser pulse energy is increased, the amount of melt/recast also increases due to the larger thermal impact of higher pulse energy. Hence, the combination of low pulse energy, say <20μJ, and high repetition rate of 1MHz tends to be used for micromachining. The high peak power of picosecond lasers means that almost any material can be micromachined and this report gives examples of the application of high repetition rate to scribing different glass types. In contrast, drilling through holes in materials of thickness >0.5mm, requires laser pulse energy >100μJ and by controlling the laser repetition rate and laser beam manipulation high quality holes can be drilled. The reduced thermal effects of the 10 picosecond pulse duration are also essential to produce high quality drilled holes.

![Effect of laser pulse energy](image)

**Fig. 1.** Effect of laser pulse energy, $E_p$, on hole quality for laser hole drilling.

2. Fuel injection nozzles

Many high performance devices demand extremely precise control of the micro-machined part dimensions/features and one example is fuel injection nozzle drilling in the automotive industry. Presently, nozzle apertures are typically around 200μm in diameter, however, smaller diameter apertures can increase the velocity of the flow and thus promote more complete atomization of the fuel through the nozzle as it enters the combustion chamber. The resulting spray will be composed of finer droplets that will mix more effectively with the air producing more complete combustion and reduce emissions to the environment. The harsh operating conditions require the use of hard steels, resistant to wear and corrosion with typical thicknesses of 1-2mm to withstand the high fuel pressures. The diameter and shape of the fuel injection nozzles are adjusted for the desired flow rate, speed and pressure, which results in precise tolerances of the order ± 2μm, all of which can be achieved by laser.

At present, fuel injection nozzles are drilled by Electro-Discharge Machining (EDM), which is used extensively for making steel tools. One of the main inherent advantages of laser drilling is the non-contact
nature of the interaction, so there is no mechanical wearing of parts, which is in contrast to EDM machining, when there is continual wearing down of the electrode.

To drill through steel >0.5mm typically requires pulse energy >100μJ and limiting the repetition rate to <100kHz allows control of the heat affected zone. Trepanning the laser beam reduces the amount of burr or recast produced during laser drilling and the development of helical drill optics that rotate the laser beam allow high quality drilling with control of the hole taper. As indicated in the schematic in Fig. 2, helical drill optics allow the freedom to form different nozzle shapes such as (a) taperless or (b) reverse taper holes, as illustrated in Fig. 3.

**Helical Drilling – Optical Principle**

![Diagram showing helical drilling optics](image)

Fig. 2. Helical drilling optics that precess the laser beam allowing control of the laser drilled hole taper.

![Diagram showing diesel injection nozzle shapes](image)

Fig. 3. Diesel injection nozzle shapes possible by helical drill optics: (a) taperless hole and (b) reverse taper holes.
2.1. Comparison of EDM and laser drilled holes

A further advantage of picosecond lasers is that they have the capability to drill smaller hole sizes (~100μm) through 1mm steel, which is highlighted in Fig. 4 where a comparison is made of holes drilled by (a) EDM and (b) picosecond laser drilled hole using helical drill optics and helium assist gas. The pitted sidewalls produced by EDM machining are due to the high temperatures needed for erosion of the steel to occur. The optimized picosecond laser drilled holes shown here produce smoother sidewalls and entrance/exit holes using helical drill optics and helium assist gas to mitigate plasma formation that can create debris and recast.

Fig. 4. Comparison of holes drilled in 1mm thick steel by (a) EDM and (b) picosecond laser. The laser drilled holes are narrower with cleaner sidewalls.

3. Micromachining of glass

Glass is being increasingly utilized for many devices, particularly as more handheld devices include large displays. Furthermore, the relatively small size and weight of handheld devices such as tablets has allowed them to displace desktop PCs and laptops in our homes. Through holes in glass can be used for interconnects, to accommodate watch hands in wrist watch faces or allow mounting special shaped holes for mounting screws. Interconnection by glass interposers are attractive as an alternative for silicon or organic based interposers since the coefficient of thermal expansion (CTE) of glass matches with silicon dies making the package more reliable and glass is more dimensionally stable than packaging materials such as FR4. Laser machining of glass is difficult since it is highly transparent to most Diode Pumped Solid State (DPSS) laser wavelengths. Also, it is prone to cracking if the glass is heated up too quickly. However, the high peak power of picosecond lasers allows glass to be machined effectively without microcracking.

3.1. Drilling of through holes in glass

Diamond drills are most commonly used to make holes in glass (EDM being unsuitable for drilling non-conductive materials); however, it is a slow grinding process that can weaken the mechanical strength of the glass. The high peak power of a picosecond laser offers the opportunity to drill glass with little or no thermal
effects and high pulse energy $>100\mu J$ allows glass to be drilled very effectively and again control of the laser repetition rate can allow holes to be drilled with no microcracks. For example, Fig. 5 shows a SEM image of a 1mm diameter holes drilled in 1mm thick glass using 1064nm picosecond pulses and Fig. 6 shows a comparison of 4 point bend test measurements to determine fracture strength of 1mm diameter holes drilled through 1mm thick glass. The ps laser drilled through holes have almost the same fracture strength compared to the bare glass without any holes, so laser drilling has no structural weakening of the glass. Similar to the previous case of injection nozzle drilling, helical drill optics can be used to drill taper-free holes.

Fig. 5. 1mm diameter holes drilled in 1mm thick glass using 150$\mu J$, 1064nm picosecond pulses at a repetition rate of 50kHz.

Fig. 6. Comparison of fracture strength by four point bend test of 1mm glass after drilling 1mm diameter through holes using ns laser, ps laser and diamond drill.
3.2. Separation of chemically strengthened glasses by ps laser

The displays in modern smart phones and tablets demand more durable glass to prevent damage from accidental dropping or scratching. The glass can be chemically strengthened by a surface finishing process in which the glass is submersed in a bath containing a potassium salt, which causes sodium ions in the glass surface to be replaced by potassium ions from the bath solution. The potassium ions lodge into the gaps left by the smaller sodium ions, which migrate into the potassium salt solution. This replacement of ions causes the surface of the glass to be in a state of compression and the core in compensating tension. There are a number of chemically strengthened glasses on the market and the glass needs to be cut into the desired shape. Mechanical separation is not appropriate, since the stress within the glass means it is prone to shatter and cracks do not propagate in straight lines. Laser glass separation techniques have been adopted by the industry, however, these glass types are extremely challenging to cut and separate using lasers.

It is possible to separate strengthened glass by scribe and break techniques using a tightly focused picosecond laser beam. For example, Fig. 7 shows a scribe in 0.7mm thick chemically strengthened glass, where internal scribe lines are made by focusing 1064nm laser pulses to a spotsizes of 1-2μm inside the glass at a laser repetition rate of 500kHz. Three passes were made at a stage speed of 450mm/s, giving an overall scribe speed of 150mm/s resulting in the very clean sidewalls are extremely clean with sharp edges. Since, this scribe and break technique utilizes a translation stage to move the glass it is compatible with large glass panel sizes >1m², allowing manufacturers to reduce costs by producing more individual displays per panel.

![Chemically strengthened glass separated using a scribe and break technique by 1064nm, 6μJ, 500kHz pulses at a net process speed of 150mm/s.](image-url)

Fig. 7. Chemically strengthened glass separated using a scribe and break technique by 1064nm, 6μJ, 500kHz pulses at a net process speed of 150mm/s.
3.3. Cutting of thin (<200μm) glass by ps laser

To reduce size and weight of displays further, thin glass <200μm can be used for interior LCD or touchscreen layers within displays. Such thin glass is very sensitive to laser irradiation and ultraviolet wavelength is then the best choice for cutting/machining. The improved optical absorption and smaller focused spotsizes achievable with ultraviolet wavelength being essential to preventing microcracking. Figure 8 shows an example of 50μm thick glass scribing using 500kHz, 355nm pulses to produce a half depth scribe at a speed of 125mm/s.

![Fig. 8. 50μm thick glass scribed using 355nm pulses at a speed of 125mm/s.](image)

4. Biobabsorbable stent cutting

Over half a million stents per year are used in the US alone to prop open blood vessels. One complication of early, all-metal stents was restenosis, where plaques form on the stent, re-blocking the opened blood vessel. In response, stent manufacturers developed a second generation of stents which were coated with a bioabsorbable plastic containing an anti-restenosis drug. As the coating dissolves over months, this drug slowly elutes on-site. However, there are still potential long-term, post-operative complications (POCs) with these stents and so bioabsorbable materials have been developed, which disappear completely after providing a support framework over the critical months after vessel opening.

The polymers used in these stents must be strong enough to withstand physical stresses within the body and there are already many types of bioabsorbable materials that meet this criterion, Törmala, 1998. These materials are extremely thermally sensitive, which in combination with the extremely high precision (<20 μm) required to manufacture the stent structure makes laser micromachining about the only choice for this task. The improved optical absorption available at deep UV wavelengths means that excimer lasers have been a frequent choice for micromachining polymers. However, an emerging alternative approach is to use UV (355nm) picosecond pulses focused to a small spot size (10 μm or less), which facilitates higher optical
absorption in a small localized area. By this strategy, high quality through cuts can be made in these materials and Fig. 9 illustrates cuts have been made in poly (L-lactic acid) material (PLLA) using 355 nm picosecond pulses.

Fig. 9. Cuts through 200μm PLLA bioabsorbable tubing using 10μJ, 355nm picosecond pulses.

5. Conclusions

High aspect ratio fuel injection nozzles can be drilled in 1mm steel using picosecond laser pulses showing better quality compared to the existing EDM technology. Very high quality holes can also be drilled in 1mm thick glass with no effect on the mechanical strength of the glass. High repetition rate of the order 1MHz are useful for scribe and break techniques in a number of different types of glass types and thicknesses at process speeds of >100mm/s. Furthermore, the combination of short pulse duration and ultraviolet wavelength is ideal for machining transparent polymer materials with minimal heat affected zones.

References
