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Femtosecond versus picosecond laser ablation

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ABSTRACT

Results of ablation of different materials by femtosecond and picosecond laser pulses are compared. Advantages and disadvantages of both laser systems are discussed. Two most important criteria, processing speed and quality of the fabricated structures, are addressed. High repetition rate picosecond lasers allow high speed cutting of thin metal foils and silicon wafers, whereas for micro-drilling it is more advantageous to use femtosecond laser systems.
Keywords: Ultrashort laser pulses, material processing

1. INTRODUCTION

At present, applications of ultrashort laser systems for high-quality processing of different materials are very rapidly growing. The overwhelming majority of the research groups working in this field are using Ti:Sapphire femtosecond laser systems with 1 kHz repetition rate. Ti:Sapphire laser systems are pumped by visible laser radiation, which is usually provided by frequency-doubled diode-pumped solid-state lasers. Novel femtosecond lasers are based on ytterbium tungstate (Yb:KGW) or other materials and can be directly pumped by laser diodes. For example, the Eclipse model developed by Spectra Physics is directly diode-pumped femtosecond laser system with the output power of up to 4 W operating at a wavelength of 1048 nm at repetition rates up to 7 kHz. Other research organizations and companies are also working on the development of direct diode-pumped femtosecond laser systems. In spite of very rapid progress in this field, femtosecond laser systems are still quite expensive and complex, which retards their acceptance by the industrial end users. There are some optimistic expectations that picosecond lasers will be able to provide the same processing quality and fit into the industrial environment.

Principle setups of the modern femtosecond and picosecond laser systems are shown in Fig. 1. In both cases oscillator and amplifier systems can be pumped by diode lasers. For the generation of femtosecond pulses an additional pulse stretcher and compressor are used. Compared to femtosecond lasers, picosecond lasers are more simple and promise to be more cost effective. Today both systems demonstrate the same operation stability.

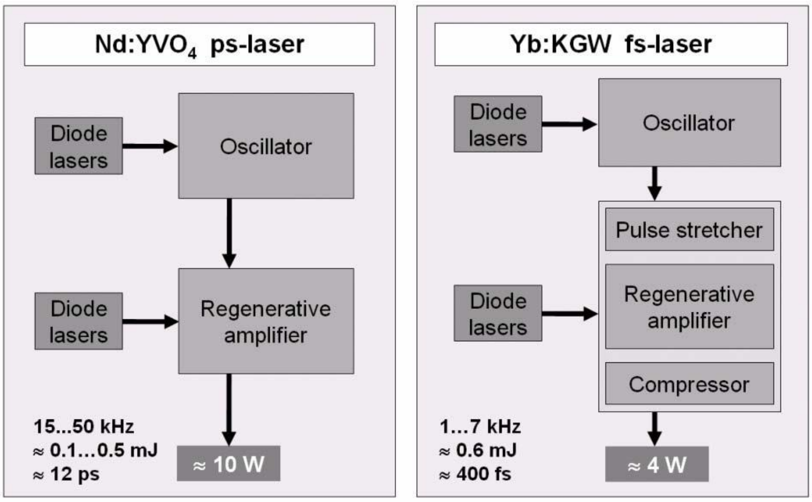

Figure 1. Principle setups of all diode-pumped picosecond and femtosecond laser systems.

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The aim of this work is to provide a fair comparison of material processing results that can be obtained with femtosecond (Clark MXR CPA 2001) and picosecond (Lumera STACCATO) laser systems. Both lasers are oscillator-amplifier systems. The femtosecond laser consists of a frequency doubled stretched-pulse mode-locked Erbium doped fiber oscillator [1] and a Ti:Sapphire regenerative amplifier using the chirped pulse amplification technique [2]. The picosecond laser consists of a passively mode-locked picosecond $Nd:YVO_4$ oscillator with a semiconductor saturable absorber mirror, a pulse picker, and a $Nd:YVO_4$ regenerative amplifier [3]. Detailed characteristics of these laser systems are provided in Table 1. For comparison of material processing results focal spot sizes for both laser systems have been adjusted and kept the same at the diameter of 30 µm.

Specifications	**Lumera STACCATO**	**Clark MXR CPA 2001**
Wavelength	1064 nm	775 nm
Laser material	$Nd:YVO_4$	Ti:Sapphire
Pulse duration	12 ps	130 fs
Average power	7.5 W	0.8 W
Repetition rate	50 kHz	1 kHz
Pulse energy	150 µJ	800 µJ
Beam quality	$M^2 < 1.5$	$M^2 < 1.5$
Focal spot	30 µm	30 µm

Table 1. Characteristics of picosecond and femtosecond laser systems which have been used in this work.

It is well-known from investigations of the pulse-width dependence of the damage threshold [4] that for metals and laser pulse durations below 100 ps, the damage threshold (determined by the laser pulse fluence) is practically independent of the pulse width. In practical applications, when a high processing speed is required, laser fluences well above the damage threshold are used. In this case the energy introduced into the material and the corresponding thermal load are high. Therefore, it could be expected that the ablation results for 100 fs and 10 ps pulses will be the same. Moreover, there are some considerations suggesting that laser pulses with 10 ps pulse duration are ideal for micromachining applications [5]. The main argument [5] is that in case of subpicosecond laser pulses nonlinear effects in air (optical breakdown, filamentation, etc.) are very disturbing for material processing and do not allow to reach the same precision and processing quality that eventually can be obtained with picosecond pulses. It is of course well-known that nonlinear effects play more important role for subpicosecond pulses. But it is misleading to consider this effects as disturbing and to think that with picosecond lasers one can get better processing quality than with femtosecond laser pulses. By simply placing the focus of femtosecond laser pulses into the workpiece (not above the surface), one can benefit of these nonlinear effects for high-quality material processing [6].

In recent paper [7] the laser-ablated volume and depth have been investigated as a function of laser pulse duration. It has been shown that the ablated volume from an aluminum target had a flat maximum for subpicosecond pulses and a minimum for 6 ps pulses. The ablated depth had a plateau for subpicosecond pulses and monotonically decreased for longer pulses. The same behavior has been observed earlier with other metals [8, 9]. Therefore, when the same energy, repetition rate, and laser wavelength are used, usually femtosecond lasers allow faster processing than picosecond laser systems.

2. EXPERIMENTAL RESULTS

In our experiments, the laser systems shown in Table 1 have been used for drilling and cutting of different materials. For laser processing of metals and other materials with high heat conduction both laser systems can be applied. Due to higher repetition rate of the picosecond laser system one can get correspondingly higher processing speed. For poor heat conductors the high repetiton rate can become a problem.

In the first set of experiments, the number of pulses required to drill a through-hole in 100 µm, 500 µm, and 1 mm steel using femtosecond and picosecond laser systems are measured. The results for 100 µm and 500 µm are shown in Figs. 2, and 4 respectively.

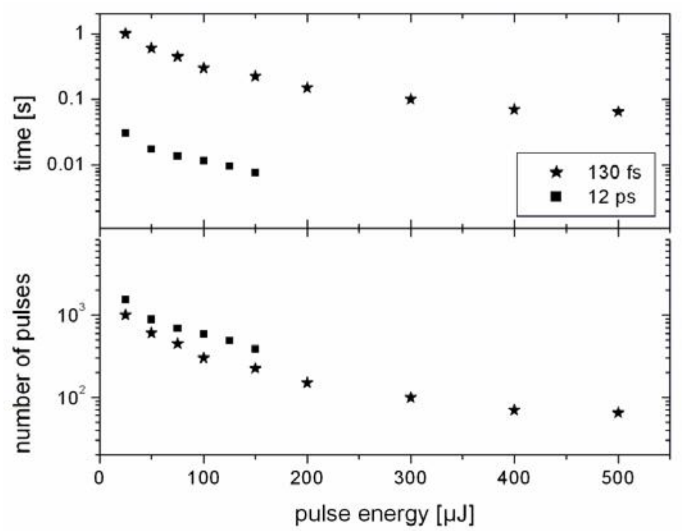

Figure 2. Number of pulses and time required to drill through 100 μm thick steel foil.

It is observed that when the same laser pulse energy is used, the number of pulses required to drill a through-hole is larger in case when picosecond laser system is applied. However, the processing speed is faster due to the 50 times higher repetition rate. When the highest pulse energy which can be provided by both laser systems is used, we get the data given by the last points on the two curves shown in all figures. For 150 μJ picosecond vesus 500 μJ femtosecond laser pulses, the number of the required pulses is 6 times higher, but the through-hole drilling speed is 8 times faster.
To obtain better hole quality it is always necessary to apply more laser pulses than it is used for the drilling of the through-hole. These subsequent laser pulses produce a "polishing effect" which has been discussed in details in [6]. Corresponding results for both laser systems are shown in Fig. 3.

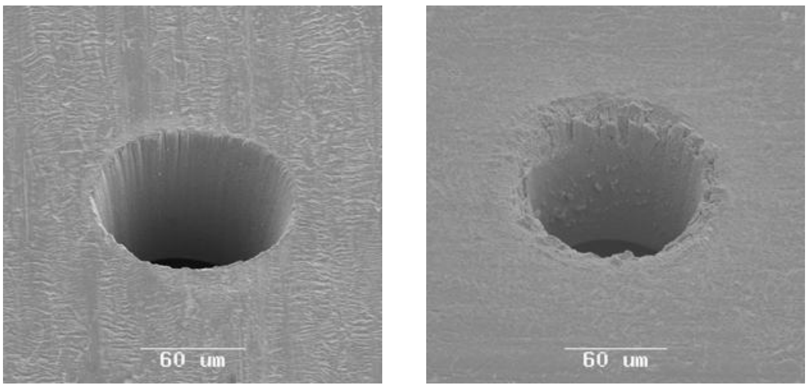

Figure 3. Scanning electron microscope (SEM) images of holes drilled in 100 μm steel by trepanning technique using 25 μJ femtosecond (left) and 40 μJ picosecond (right) laser pulses. Total processing time was 25 s in both cases.

The hole drilled by femtosecond laser pulses has obviously better quality, and the "polishing effect" works better in this case. In Fig. 4, results obtained for drilling through-hole in a 500 μm steel are shown.

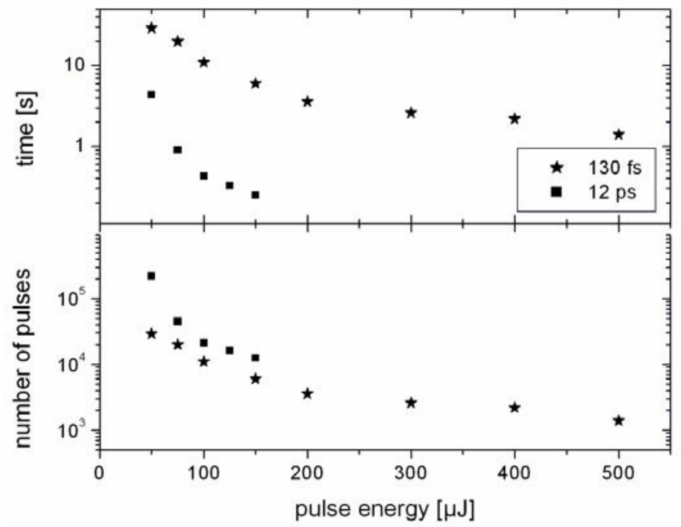

Figure 4. Number of pulses and time required to drill through 500 μm thick steel plate.

For 150 μJ picosecond vesus 500 μJ femtosecond laser pulses, the number of the required pulses is 9 times higher, but the through-hole drilling speed is approximately 6 times faster. In Fig. 5, SEM images of the corresponding through-holes are shown.

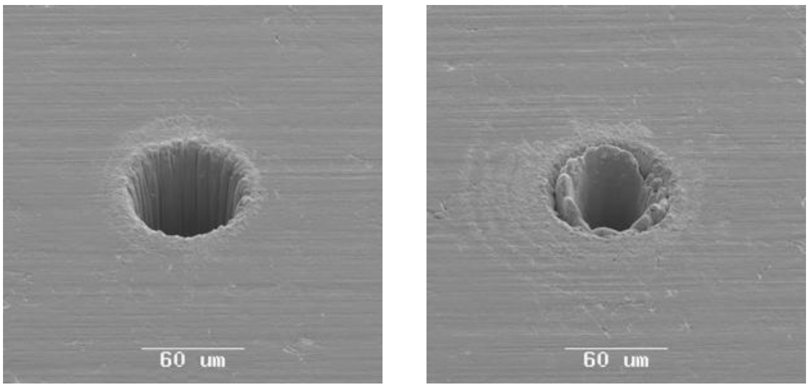

Figure 5. SEM images of the through-holes drilled in 500 μm steel by femtosecond (left) and picosecond (right) laser pulses.

These through-holes have been fabricated by 400 μJ femtosecond pulses during 2.2 s and by 125 μJ laser pulses during 0.32 s. Much better results can be obtained when trepanning and "polishing" technique are applied (see Fig. 6). To fabricate these holes total processing time of 30 s was required.

By considering results for drilling through 1 mm thick steel plate, we observe that with growing plate thickness it is more and more difficult to drill a through-hole with lower energy picosecond pulses. The number of the required 150 μJ picosecond pulses is 16 times higher than 500 μJ femtosecond laser pulses, but still the total drilling time is 3 times shorter. We also observe that thermal load and heat affected zone become larger in case when 50 kHz picosecond laser system is used. In Fig. 7, microscope images of 800 μm x 800 μm square structures fabricated in 100 μm steel foils by picosecond laser pulses are shown. One can see that the heat-affected zones, which appear as a brown-blue edge around the structures, can be readily observed when picosecond laser pulses are applied. Therefore, to produce high-quality cuts with picosecond lasers, one is forced to use high scanning speed, low pulse energy, and thin samples. In Fig. 8, a comparison of the cutting results produced by femtosecond and picosecond laser pulses is given. As before, extra processing time is required for “polishing” to obtain higher cutting quality. In both cases quality of the processing results is similar. Therefore, high speed cutting of thin metal foils can be a very good application of picosecond lasers.

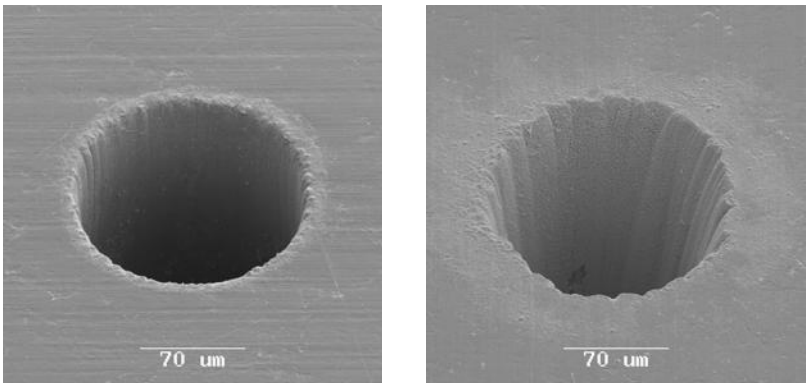

Figure 6. SEM images of holes drilled by trepanning technique in 500 µm steel using 500 µJ femtosecond (left) and 150 µJ picosecond (right) laser pulses. Total processing time was 30 s in both cases.

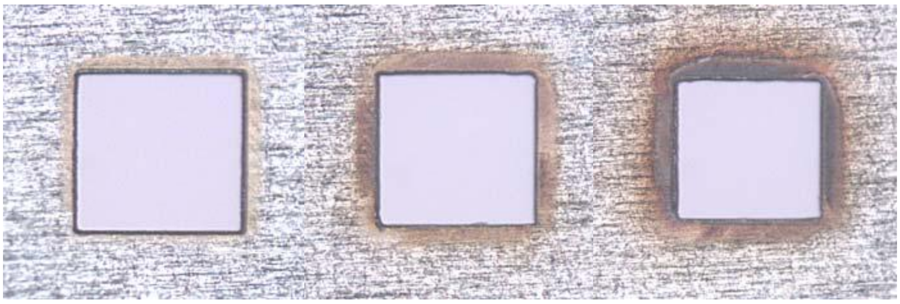

Figure 7. Microscope images of structures fabricated in 100 µm steel foils by picosecond laser pulses with a scanning speed of 1200 mm/min using 15 µJ, 50 µJ, and 150 µJ laser pulses. The total processing time was set 30 s.

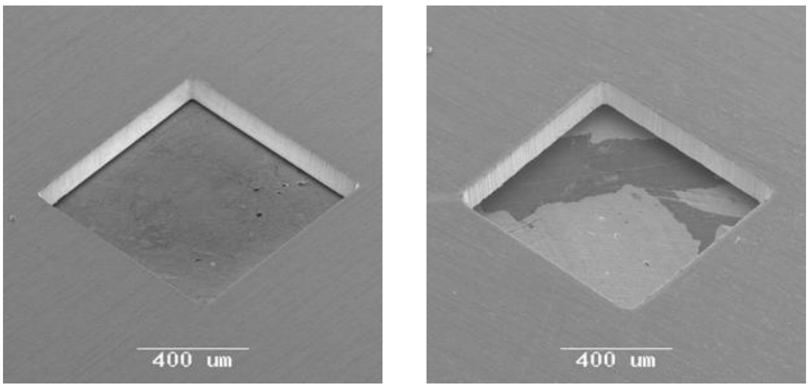

Figure 8. SEM images of cuts fabricated in 100 µm steel foils by 30 µJ femtosecond laser pulses (left) with a scanning speed of 10 mm/min and processing time of 3.4 min and 15 µJ picosecond laser pulses with a scanning speed of 1200 mm/min and processing time of 1.2 min.

Below we demonstrate our results for processing of silicon wafer using femtosecond and picosecond laser systems. Laser cutting of thin silicon wafers and drilling of small holes has large economic significance in microelectronic industry. As in the experiments described above, we first measured the number of pulses and time required to drill a through-hole in 100 μm, 500 μm, and 1 mm silicon wafers. Our results for 100 μm and 500 μm thick silicon plates are shown in Fig. 9.

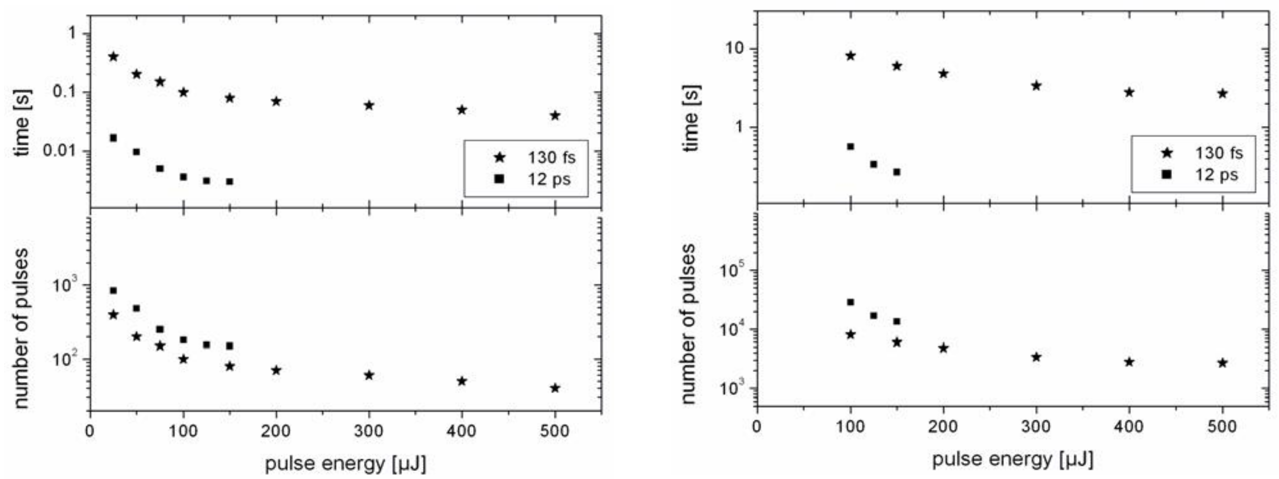

Figure 9. Number of pulses and time required to drill through 100 μm (left) and 500 μm (right) thick silicon wafers.

Again, when the same laser pulse energy is used, the number of pulses required to drill a through-hole is larger in case when picosecond laser system is applied. However, the processing speed is faster due to the 50 times higher repetition rate. When the highest pulse energies are used, i.e. 150 μJ picosecond laser pulses vesus 500 μJ femtosecond laser pulses, the number of required pulses is 4 times higher and the drilling speed is 13 times faster in case of 100 μm silicon wafer, whereas for 500 μm wafer the number of required pulses is 5 times higher and the drilling speed is 10 times faster. Thus with the 50 kHz picosecond system one can drill a through-hole in a thin silicon wafer at least 10 times faster than with the 1 kHz repetition rate femtosecond laser. But there is a big difference in hole quality as shown in Fig. 10. The hole produced by picosecond laser has obvious traces of molten and resolidified material due to much higher thermal load in this case. We should mention here that for drilling of high quality holes application of high repetition rate laser pulses (50 kHz and above) is not a good strategy especially when these holes become deep. A better strategy would be to increase the laser pulse energy instead of the pulse repetition rate.

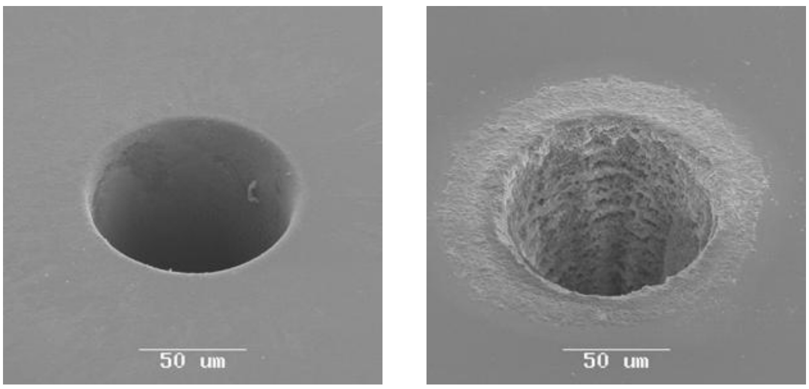

Figure 10. SEM images of holes drilled by trepanning technique in 500 μm silicon wafer using 300 μJ femtosecond (left) and 150 μJ picosecond (right) laser pulses. Total processing time was 60 s in both cases.

High repetiton rate picosecond laser systems can be successfully used for high speed cutting purposes, when the thermal load can be redistributed across a large area. In Fig. 11, cuts fabricated by different laser systems in 200 μm thick silicon wafer are shown. The chosen processing parameters corresponds to the best quality which has been obtained.

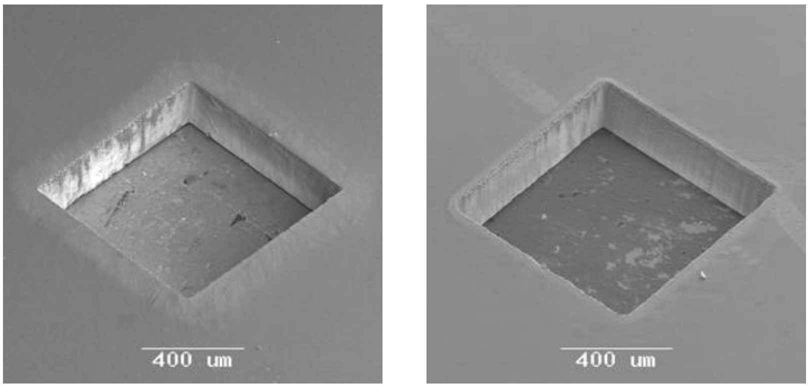

Figure 11. SEM images of the cuts fabricated in 200 μm silicon wafer by 100 μJ femtosecond laser pulses (left) with a scanning speed of 10 mm/min and processing time of 9.6 min, and by 60 μJ picosecond laser pulses with a scanning speed of 600 mm/min and total processing time of 2.6 min.

Using picosecond lasers, practically the same cutting quality as with femtoseocnd laser systems can be obtained. Moreover, this work can be done at higher speed. This is very important aspect for practical applications and demonstrates that picosecond lasers have good potential in certain industrial sectors.

In our previous work on ultrafast laser processing, we and other groups in the world demonstrated that femtosecond lasers provide a universal tool for processing of arbitrary materials. This is certainly not the case when high repetition rate picosecond lasers are applied. When 50 kHz picosecond laser are used to process poor heat conducting materials or transparent dielectric materials, results can be very disappointing. An illustrative example is shown in Fig. 12, where cutting results for 100 μm glass are shown. The thermal load produced by picosecond laser system in glass is too high, which results in undesired effects and even glass breaking.

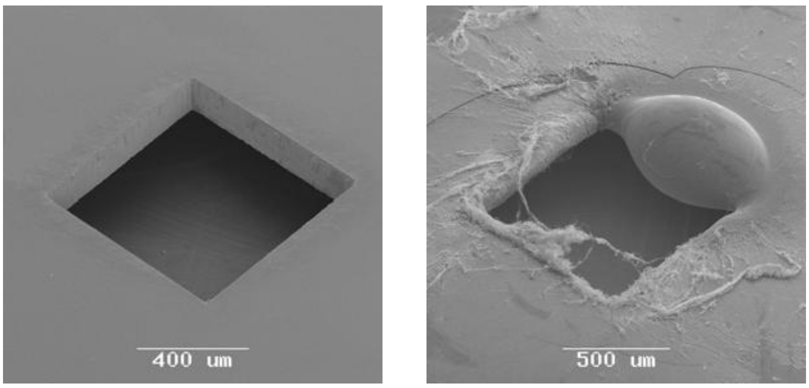

Figure 12. SEM images of the cuts fabricated in 100 μm glass by 200 μJ femtosecond laser pulses (left) with a scanning speed of 10 mm/min and processing time of 3.2 min, and by 60 μJ picosecond laser pulses with a scanning speed of 60 mm/min and total processing time of 5.3 min.

It is necessary to keep in mind that interaction of ultrashort laser pulses with transparent materials is strongly nonlinear, which requires simultaneous absorption of several photons to overcome the energy band gap and to initiate ablation. This makes femtosecond laser systems (due to 100 times shorter pulse duration and higher intensity) more efficient compared to 12 picosecond laser systems used in these studies.

3. CONCLUSION

In this work we have tried to provide a fair comparison between commercially available 130 femtosecond and 12 picosecond laser systems with respect to their advantages and disadvantages in the most important material processing applications like drilling and cutting.

1) High-repetition rate picosecond lasers systems produce a higher thermal load during the drilling process, therefore quality of micro-holes fabricated with femtosecond lasers is generally better. We should mention that for faster drilling of high-quality holes a better strategy would be to increase the laser pulse energy instead of the pulse repetition rate, and it would be more advantageous to apply higher energy femtosecond pulses. Therefore, in high quality micro-drilling applications femtosecond laser processing probably will be a leading technology.

2) To produce high-quality cuts with high-repetition rate picosecond lasers, one is forced to use very high scanning speed, low pulse energy, and thin samples. In this case the total thermal load produced by laser irradiation can be redistributed across a larger area. Using 50 kHz picosecond lasers one can produce high-quality cuts in thin metal films, silicon wafers, and other good heat conducting materials at higher processing speed than it can be done with femtosecond laser systems. In this important processing field picosecond laser processing probably will be a leading technology.

3) In case of processing of transparent materials femtosecond lasers are out of concurrence.

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