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Improving the quality of the of the microchannel fabricated by picosecond laser pulses spatially shaped with cylindrical lens

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Abstract

Microchannels have applications in heat sinks, liquid dosing, flow rate measurements and structuring of surfaces for tribological applications. Laser ablation with picosecond pulses promises small melt formation and precise machining of the metals. However, the pulse heat accumulation can reduce the advantages of picosecond machining. Beam shaping strategies are able to improve the machining quality through manipulation of the heat accumulation. In the current work, microchannels were produced on the surface of milled stainless steel samples. A combination of a cylindrical lens with a plano-convex lens was used creating a line focus on the sample surface up to the length of 500 µm. The experiments were performed with a 1 µm-wavelength picosecond laser with repetition rates of 50 kHz and 100 kHz. The maximum pulse energy of 188 µJ yields fluence about twenty times above ablation threshold. The geometrical properties of the microchannels obtained were compared with the result of conventional processing with a circular spot with respect to the width and depth, sharpness of profile. Beamshaping with a cylindrical lens allows improving the quality of microchannels, narrower microchannels and reduction of debris.

Keywords: Ablation, Drilling and Micro-cutting, Microchannel.

1. Introduction

The strongly increasing demand for efficient manufacturing of microchannels is e.g. caused by the rapid development of microdevices such as microchannel heat sinks (see Kadam, S. 2014), microchannel reactors in fuel-cell systems (Thormann et al., 2009), grooving in solar cell panels (Fernandes et al., 2013), liquid dosing (Richter et al., 1997), and friction reduction in tribological surfaces (Costa and Hutchings, 2009). For instance, microchannels in heat sinks can effectively cool down the ICs in computer modules or mirrors in high energy lasers (Haishan et al., 2010). Two significant applications of microchannels are in the steam reforming of hydrocarbons in fuel cells and scribing of microchannels in ZnO/ITO for the serial connections in solar cells. In all of these applications, a constant aspect ratio (the ratio of the structure depth to the structure width), sharp edges profile, clean walls, and short manufacturing time are the key features. Several methods have been reported for manufacturing of microchannels including chemical etching, electrical discharge machining, lithography-based techniques and laser micromachining. However, each of these methods has their specific disadvantages: Chemical etching needs long removal time (≈1µm/min for steel) and suffer from limited control of the depth of the channels. Electrical discharge machine offers high dimensional precision but suffers from a low material removal rate. Lithography-based techniques generally require multi-step processing which increase the manufacturing costs. Laser micromachining, on the other hand, promises a solution for fast, low-cost, and accuracy requirements.

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Laser micromachining of microchannels has been studied by some research groups. These works can be categorized into laser etching and direct laser writing on the surface. In laser etching a liquid etchant assists the material ablation by an induced thermochemical reaction that dissolves the material. Although an aspect ratio of up to 10 is achieved, the quality still does not meet the requirements, especially for a good reaction performance of hydrocarbon steam reforming in fuel cells or laminar flow in the heat sinks (Oh et al., 2006). Boiling of the etchant under laser radiation is the main cause of reduced quality in laser etching of microchannels. In direct laser writing on the surface, picoseconds laser pulses have been widely adopted, as laser ablation with picosecond pulses promises small melt formation and precise machining of the metals. However, the pulse heat accumulation can reduce the advantages of picosecond laser machining. The accumulated heat can increase the local temperature up to melting point which changes the morphology of the ablated area (Weber et al., 2014). In addition, the accumulated heat reduces the ablation threshold which influences the dimensions of the channels (Niso et al., 2014). However, there is an optimal laser fluence of about five times the ablation threshold. (Neuenschwander et al., 2012).

This paper presents a comparison of microchannels produced by a conventional circular cross-section beam and a beam which was shaped using a combination of a cylindrical lens with a plano-convex lens creating a line-shaped cross-section of the beam on the surface of stainless steel samples. The dimensions and qualities of the produced microchannels are compared and discussed as followings.

2. Experiments

The experiments were performed with a Duetto laser system which emits ultrashort pulses with duration of 12 ps at the wavelength of 1064 nm, with linear polarization. The average powers of 9.4 W and 11.2 W were measured at the pulse repetition rates of 50 kHz and 100 kHz, respectively. The raw laser beam which has initially the M^2 factor of 1.3, was enlarged by a beam expander to the beam diameters of 5.0 mm or 8.5 mm before passing through the focusing lenses.

The combination of a cylindrical lens with the focal distance of 150 mm and a plano-convex lens with the focal length of 60 mm were used to shape the collimated beam to a line-shaped focus on the workpiece surface, in the following called "line-beam". The collimated beam first passes through the cylindrical lens. The distance between the two lenses was set to 85 mm.This leads to a beam of 500 µm x 22 µm on the sample. Both lenses had antireflection coatings for the wavelength of 1 µm. The curvature of the plano-convex lens was set to the side of the sample in order to reduce internal reflections between the lenses hitting the sample. For the conventional circular beam, a plano-convex lens with a focal distance of 125 mm was used. This lens can focus the collimated beam of 8.5 mm to a focused beam diameter of 25 µm. This value is approximately similar to the width of the line beam shaped by the combined lens.

The samples which were used in this work had the dimensions of 60 mm×45 mm×12 mm made from stainless steel and their surfaces were milled. The microchannels were then produced while the samples were moved by a linear translation stage parallel to 45 mm edge of the samples. So, microchannels with a length of 45 mm were produced. To equalize the line energy (i.e. input laser energy per processed unit length) for the line-beam and circular beam in the two above-mentioned configurations, two different speeds were chosen. As $E_1/l_1 = E_2/l_2$ is the criteria for equalization of two energy lines, then it leads to $V_1 \cdot l_1 = V_2 \cdot l_2$, for the same repetition rate and pulse energy. Here, E_1 is the total energy emitted from the laser to produce a definite microchannel length with the circular beam, l_1 is the diameter of the circular beam and V_1 is the scanning speed for circular beam. Similarly, E_2 is the total energy emitted from the laser to produce a definite microchannel length with the line beam, l_2 is the length of the line beam and V_2 is the scanning speed for line beam.

Considering the ablation threshold of stainless steel of about 0.1 J/cm², (Neuenschwander et al., 2012), the applied fluence with the circular beam is about hundreds of times higher than ablation threshold. For the beam line, this value is only in the order of twenty times higher. The parameters which were used for processing with the circular beam and line-beam are summarized in Table 1.

Table 1. The parameters used to produce microchannels with two different beam shapes and repetition rates of 50 kHz and 100 kHz.

beam shape	beam area (µm²)	scanning speed (mm/min)	applied fluence/threshold fluence
circular beam	$\pi(25/2)^2$	12000	361 (for 50 kHz) 215.4 (for 100 kHz)
Line beam	500x22	600	23.5 (for 50 kHz) 14 (for 100 kHz)

Each parameter set was used six times with 1, 2, 4, 8, 12, 18 scans in order to investigate the effect of multiple scans on the depth and width. Subsequent to laser processing, all of the samples were ultrasonically cleaned for 5 minutes to clean the surface from debris or any dirt. Cross sections of the samples were polished afterward and the dimensional analysis of the samples was performed by a scanning electron microscope with the magnification of 600x.

3. Results

In Fig 1(a) and (b) the width and depth of the produced microchannels are presented. In Fig 1(a) it is seen that processing with the circular beam results in a relatively large variation of the width of the microchannel with respect to the number of scans. As the focused beam diameter in this case was 25 µm (shown as a dashed line), it is seen that for low numbers of scans, the microchannel widths are smaller than the beam diameter but it exceeds the focused beam diameter as the number of scans increases. In contrast to the circular beam, processing with line-beam leads to narrower microchannels and also to a smaller increase of the width with an increasing number of scans.

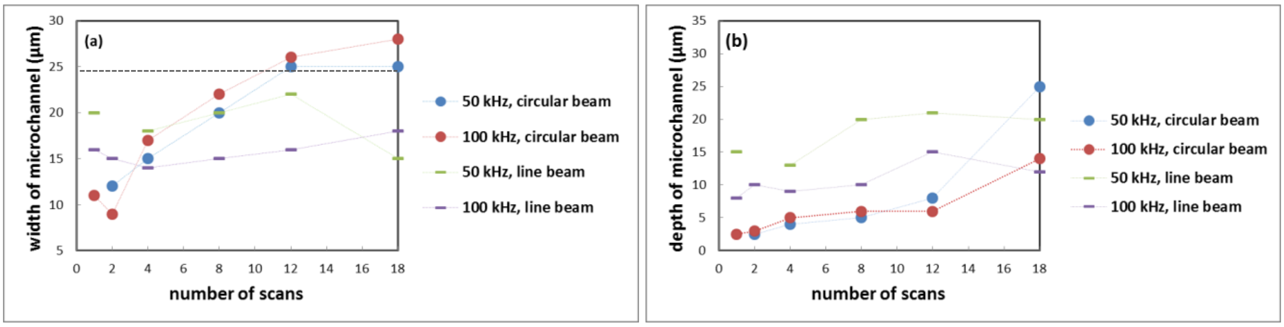

Fig. 1. (a) Width and (b), depth of the microchannels with circular and line beams in two different repetition rates and different number of scans.

In Fig 1(b), processing with circular beam and low number of scans does not show any significant depth, even at a pulse overlap of 80% and 90% (for 50 kHz and 100 kHz, respectively). However, for the same number of scans in case of the line-beam, a considerable depth is achieved. With the circular beam, each point is only irradiated by two laser pulses in every single scan, while with the line-beam, each point is irradiated 120 and 250 times (for 50 kHz and 100 kHz, respectively) with low fluence laser pulses. In processing with the line-beam, the depth of the microchannels is considerably deeper already after the first scan up to about 8 times. However, after 18 scans, the depths of the microchannels are the same for the circular and the line-beam.

Scanning electron microscopy images of the processed surfaces with the repetition rate of 100 kHz are shown in Fig. 2. For comparison of the quality, the images in the left column show the samples processed by circular beam and relatively high scanning speed and the images on the right column were processed by line -beam with equal energy per line.

For the circular beam, the evolution of the morphology of the microchannels significantly changes as the number of scans is increased. In the first four scans there is not any noticeable ablation on the surface. Increasing the number of scans leads to formation of rough morphology on the surface. This rough surface increases the energy coupling of the laser radiation into the material and leads to considerable increase of depth for further number of scans.

In contrast to processing with the circular beam, the morphologies of the microchannels are constant when processing with the line-beam as the number of scans increase. There is only few molten material in the microchannels yielding a strongly improved quality of the microchannels.

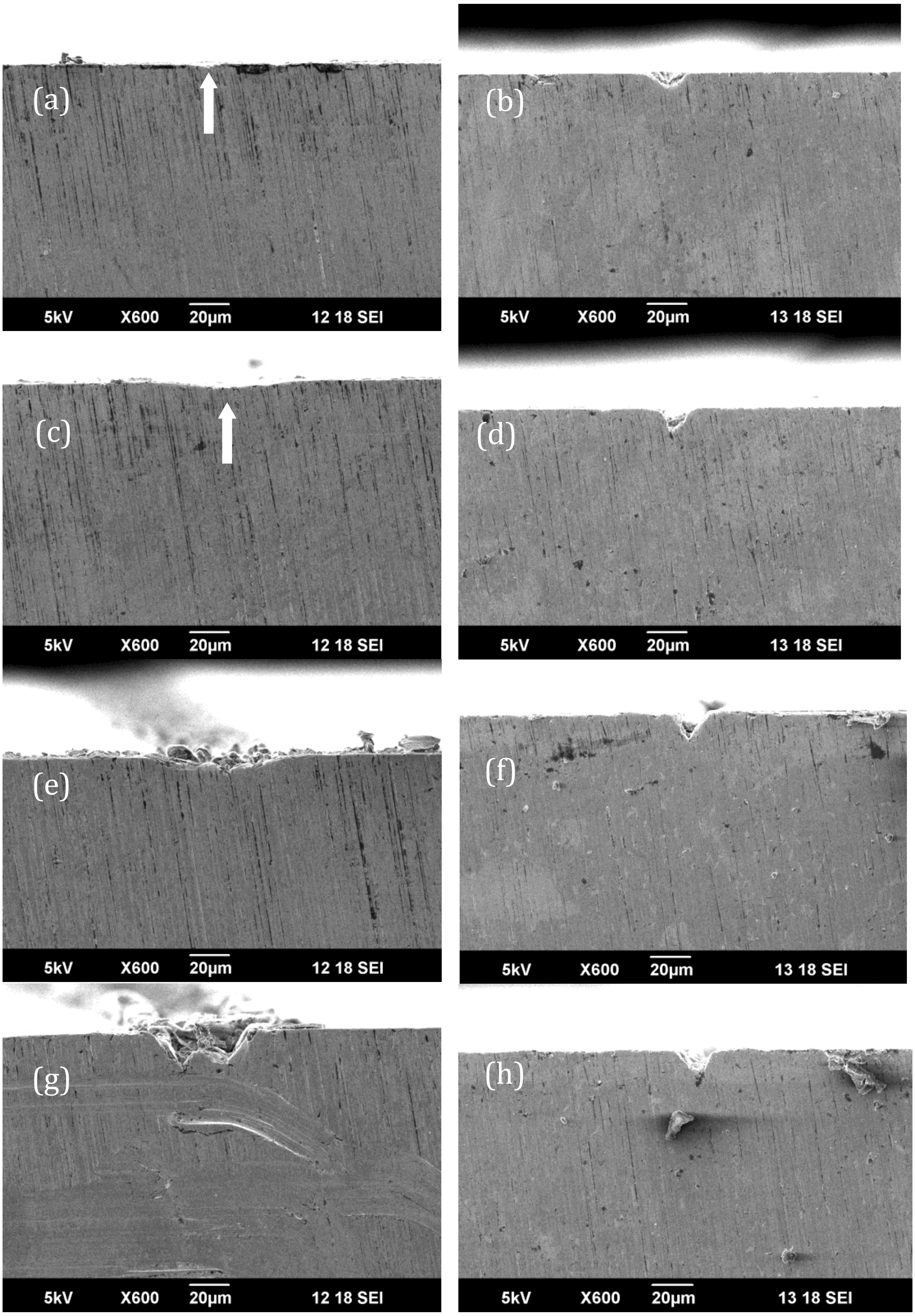

Fig. 2. Cross-sections of microchannels produced with the circular beam (left) and significantly improved quality of the microchannels produced with the line-beam (right) for different number of passes. (a) and (b): one pass, (c) and (d): four passes, (e) and (f): twelve passes and (g) and (h): eighteen passes.

4. Conclusion

In this study, dimension and quality of microchannels produced with two beam shapes are investigated: a circular beam and a line-beam. It was shown that shaping the focus from a circular to a line-beam significantly improves the quality of picosecond-laser pulse produced microchannels. In case of circular beam, each point on the sample is irradiated with only two high fluence laser pulses, while in line-beam two hundreds low fluence laser pulses hit each point. The line-beam presented another advantage of producing narrower microchannels. In addition, it was shown that the ablation rate was up to 8 times higher in the first few scan passes.

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