Micro structuring with highly repetitive ultra short laser pulses

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For the first time an industrial high repetition ultra short laser source with pulse lengths less than 250fs, high beam quality $M^2$ better than 1.2, high pulse energies up to 8µJ, and repetition rates up to 25MHz (IMPULSE, Clark-MXR, Inc.) is applied for micro material processing. First results of stainless steel machining are presented to demonstrate the possibilities and limits of the machining process with high repetition laser pulses. Because of relatively high pulse energies at high pulse repetition rates completely new effects of laser material interaction are obtained. Principle mechanisms of heat accumulation and plasma or particle shielding processes are derived from experimental results, and models are discussed. Finally, formation of self organized laser induced micro structures is shown and the influence of machining parameters is presented.

Keywords: femtosecond laser ablation, laser micro structuring, ultrafast laser machining, ultra short laser pulses, heat accumulation, laser induced micro structures, ripple structure, conical structure

1. Introduction

Since the beginning of the implementation of the ultra short pulse laser technology in the fields of micro material processing in the middle of the 1990s its areas of application, e.g. micro structuring, micro cutting or micro drilling as well as laser material interaction have been studied and described systematically [1-4]. The material processing depends on different laser and processing parameters such as laser power, laser pulse energy, laser repetition rate, processing velocity, and the number of laser pulses per area. For laser material processing the laser pulse duration is another important parameter. When a laser beam hits the material surface it preferentially interacts with valence and conduction electrons. The thermal diffusion of the absorbed optical energy into the material takes place via electron – electron-, electron – phonon, and phonon – phonon – coupling effects [5]. In this case laser pulse duration determines the energy absorbed by the material and influences the result of the laser machining process. So during laser processing with various laser pulse durations different effects onto the mechanism of laser material interaction can be expected. The pulse duration of q-switched short laser pulses of some nanoseconds up to a few micro seconds is longer than the heat diffusion time which leads to the diffusion of the laser deposited optical energy in terms of heat. This heat flow causes a reduction of the energy that was absorbed in the immediate spot of laser material interaction and leads to extensive melting and boiling of the irradiated material. The boiling ejects particles and molten material from the laser machined spot and contaminates the material surrounding the processed area. Another effect resulting from heat diffusion is a heat affected zone encircling the laser spot with thermal modified material properties. Molten material and particles expelled from the area of laser activity are deposed in its immediate surrounding which is also affected by the heat flow.

The extension of the melting into the heat affected zone, and the deposition of material debris onto a large area around the laser working spot account for the poorer accuracy of laser machining with short laser pulses in comparison to laser processing with ultra short laser pulses. In laser machining with femtosecond laser pulses the pulse duration is shorter than the heat diffusion time. Therefore practically no thermal modification of the laser irradiated material occurs. Thus micro structures can be machined that should ideally be free of melting zones, heat influence, and thermal texture modifications. The whole laser energy is applied to a small local spot in order to achieve very high laser fluences. Besides, plasma formation occurs only after the end of the ultra short laser pulse and plasma shielding is diminished or avoided [6]. In reality – even under a femtosecond regime – there is always some heat induced into the remaining solid. Due to heat flux, however, the pauses in between successive pulses, in the order of 1ms, allow for sufficient cooling. So for an ablation regime with a limited pulse overlap accumulation of heat is negligible.

Presently the ultra short pulse laser technology is applied especially in research and development and increasingly in industrial application. The implementation of commercially available femtosecond laser systems is yet economically limited due to long process times resulting from relatively low average powers.

2. Experimental

2.1 Setup

Due to the latest developments in ultra short pulse laser technology a new laser system with repetition rates up to some MHz for micro machining could be acquired by University of Applied Sciences in Mittweida (Fig.1).
The central unit of the constructed 3D micro machining system is an entirely diode pumped femtosecond fibre laser system (IMPULSE, Clark MXR Inc.). Due to a novel oscillator amplifier arrangement it yields high repetition rates (<25MHz), high pulse energies (>8µJ) and still a high beam quality (M² better than 1.2).

**Fig.1** 3D Laser micro machining system

The experimental setup has been described in detail previously [7, 8]. Within the specified range the laser energy and the laser repetition rate can be adjusted by an external attenuator and an internal AOM respectively. Through a second (external) AOM the on/off switching of the beam that can be performed with the high rapidity that is required for micro machining processes. The positioning of the beam on the surface is achieved either through shifting of the work piece by a high resolution computer controlled X-Y table (Foerenbach) or the guiding of the beam via a deflection galvo scanning system (Hurriscan II, Scanlab). Relevant parameters of the machining system are listed in table 1:

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>wave length</td>
<td>1030 nm</td>
</tr>
<tr>
<td>repetition rate</td>
<td>0.2 ... 25 MHz</td>
</tr>
<tr>
<td>max. average power</td>
<td>14.3 W</td>
</tr>
<tr>
<td>max. pulse energy</td>
<td>8.1 µJ</td>
</tr>
<tr>
<td>min. pulse duration</td>
<td>250 fs (sech²)</td>
</tr>
<tr>
<td>M²</td>
<td>1.2</td>
</tr>
<tr>
<td>max. peak intensity</td>
<td>10¹³ W cm⁻²</td>
</tr>
</tbody>
</table>

### 2.2 Experimental procedure and parameters

First investigations for micro structuring with high repetitive femtosecond laser radiation were performed with stainless steel X5CrNi18-10 (1.43001). The experimental parameters are comprised in table 2.

<table>
<thead>
<tr>
<th>parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>beam diameter</td>
<td>17 µm (56mm f-theta lens)</td>
</tr>
<tr>
<td>pulse energy</td>
<td>2, 4, 6, 8 µJ</td>
</tr>
<tr>
<td>pulse distance</td>
<td>1.9, 3.75, 7.5 µm</td>
</tr>
<tr>
<td>line distance</td>
<td>7.5 µm</td>
</tr>
<tr>
<td>pulse duration</td>
<td>250 fs (sech²)</td>
</tr>
<tr>
<td>machining velocity</td>
<td>&lt; 10,000 mms⁻¹</td>
</tr>
</tbody>
</table>

The laser beam was deflected linearly by the galvo scanner with a maximum velocity of 10,000 mms⁻¹. With a telecentric f-theta lens (f = 56 mm) a beam waist diameter of 17 µm was obtained resulting in maximum fluences of 10¹³ W cm⁻². The line distance was selected for all investigations in the pulse repetition rate range constantly the half laser beam diameter.

### 3. Results and discussion

In order to interpret the experiments the ablation is quantified by the depth of the cavity that is produced by a single scan over the surface segment. As the probes were usually scanned several times during a process the ablation depth per scan was defined as the arithmetic mean of all scans of the respective cavity. For the discussion of the process the ablation depth is correlated with the linear energy Qₜ, an indirect or secondary parameter. It describes the irradiated energy along a unit distance of the laser beam track on the surface and is calculated by equation (1) from the primary parameters average power Pₐᵥ, pulse repetition rate f, single pulse energy Qₛₚ, and pulse distance Pd (linear distance of consecutive pulses). The pulse distance is the quotient of the scan speed v over f.

\[
Qₜ = \frac{Pₐᵥ}{v} = \frac{Qₛₚ \cdot f}{Pd \cdot f} = \frac{Qₛₚ}{Pd} \tag{1}
\]

If the pulse distance is smaller than the diameter of the beam (resp. waist) consecutive pulses overlap. In the experiments the linear energy was varied via the adjustment of the pulse energy and the scan speed. The pulse-overlap was adjusted via the repetition rate.

#### 3.1 Onset of the ablation

Ablation of the denoted stainless steel could be achieved with pulse energies of 2µJ and above. The onset of ablation can be observed from the first pulses onto an unprocessed surface. Figure 2 shows the mark of a single laser pulse with an energy of 4µJ upon a stainless steel plate.

**Fig.2** Single pulse ablation with a pulse energy of 4µJ on stainless steel

At the incidence of a single ultra short pulse (red circle) the surface shows a solidified liquid phase that could be explained with the applied regime: the pulse energies in the reported experiments by at least two orders of magnitude smaller than usual in femtosecond laser material processing. Other origins of a liquid phase on the processed surface could be condensation of ablated material.
from the vapour or plasma phase. Impurities on the surface and inhomogeneities from the fabrication of the work piece cannot be ruled out either as reasons for an inhibition of the ablation in the very first stage. Figure 3 shows the average ablation depths for a single horizontal scan after 250 successive scans with the mentioned IMPULSE laser. At otherwise constant machining parameters the ablation depth increases linearly with increasing laser pulse energy. Investigations with another laser system (Jenoptik LOS) show the validity of the linear relation between pulse energy and ablation depth also for laser machining with higher pulse energies (up to 137µJ).

The influence of varying machining parameters was investigated with rectangular ablations, generated by parallel lines, in a stainless steel surface (Fig. 4). The ablation depth of the obtained structures was determined with a digital microscope (VHX-100, Keyence Inc.).

### 3.2 Line energy per unit area and repetition rate

In the following the influence of pulse energy, pulse repetition rate, pulse distance upon the laser machining are presented. The illustrations in figure 5 show that for each repetition rate the volume of ablated material increased with the linear energy. Furthermore an influence of the repetition rate on the ablation depth can be observed (Fig. 5a). It can be interpreted as a consequence of so called “accumulation effects” that occur at faster pulse repetitions. They present the substantial difference in relation to the commonly applied femtosecond laser regimes with considerably lower repetition rates. As mentioned above even in femtosecond laser processing the work piece is heated to a certain extend. Whereas at repetition rates of 1kHz effects due to heat accumulation during successive pulses is not considerable, these effects are very explicit at rates above 1MHz, especially if there is a narrow distance between or overlap of consecutive incidents. Therefore an increased repetition rate at otherwise constant operation parameters effects a rise in mean temperature of the processed material segment and thus for the coefficient. Both, thermal activation and rise of number of pulses per area [9] at constant repetition rate, raise the absorptivity and accelerate the ablation process.

In terms of ablated volume per scan, this very effect can also be achieved by a higher repetition rate and a reduced ablation threshold at a constant number of pulses per area.

### Fig. 3 Ablation depth depending on pulse energy

![Ablation depth depending on pulse energy](image)

The ablation depths reached with repetition rates between 2.5…25MHz are presented in figure 5b. Up to 5MHz the ablation depth increases. For repetition rates beyond that, reduced ablation was observed. Several causes could possibly be made responsible for this: At first, up to a repetition rate of 2MHz the maximum single pulse energy of 8µJ produced by the laser. At higher pulse rates the maximum pulse energy decreases. Above 7MHz the maximum pulse energy is lower than the ablation threshold for single pulse ablation of the stainless steel deter-
mined. At second, the treatment of the surface with high pulse repetition rate laser radiation is obstructed by a shielding of the incident laser radiation by the plasma and the ablation cloud of the previous pulse. Particle shielding effects were determined already during processing with high repetition ultra short laser pulses [10]. Figure 6 shows the dependence of the ablation rate on the pulse rate which is in turn a function of the pulse energy, the heat accumulation effect, and the plasma shielding. There seems to be an ablation maximum at a repetition rate of about 5MHz. Nevertheless the possibility to maintain scan speeds of up to 7500mms\(^{-1}\) while working with repetition rates of 5MHz allows ablation depths of up to 1.8mm\(^3\)min\(^{-1}\). Thus with high repetition femtosecond laser equipments considerably higher product quality can be achieved than with industrial short pulse lasers at comparable process rates.

![Ablation rate depending on pulse repetition rate](image)

**Fig.6** Ablation rate depending on pulse repetition rate

### 3.3 Pulse distance and repetition rate

At constant linear energies the influence of the pulse distance respectively the repetition rate was investigated. The pulse distance \(P_d\) was varied with the scanner speed \(v\) whereby the pulse rate was maintained constant. In order to keep the irradiated energy per material unit segment (linear energy \(Q_s\)) constant the laser power was raised proportional to the pulse distance. Figure 7 shows the obtained ablation depths, with a constant linear energy (1.1Jm\(^{-1}\)), for different pulse distances and for different pulse repetition rates.

![Ablation depth depending on pulse distance and repetition rate at constant \(Q_s=1,1J/m\)](image)

**Fig.7** Ablation depth depending on energy per unit section

The illustration shows that the ablation depth becomes larger with shrinking pulse distance. As the linear energy is kept constant, in the regime with the largest pulse distance the highest pulse energy is applied to the material. The more rapidly the ejection takes place the more of the laser energy is turned into kinetic energy. With a small pulse distance or even at partial overlaps pulses with correspondingly smaller energies hit the material. Ejection of material is not so pronounced thereby, so that accordingly less energy is withdrawn from the work piece. Also the shielding of the following pulse is smaller due to the less developed plasma torch. Additionally the following pulse couples into material with higher temperature. So a treatment with shorter pulse distances includes altogether a higher mean temperature of the ablation site. This lowers the ablation threshold again and favours the absorption, whereby altogether higher ablation rates can be obtained. In figure 7 also the effect of different pulse repetition rates on the ablation depth is recognizable. At a pulse distance of 7.5µm it is recognizable that when working with a pulse repetition rate of 500kHz opposite to 200kHz a smaller ablation depth was reached. The cause for this behaviour could be the plasma or particle shielding effects. The rise of the ablation depth at a pulse repetition rate of 1000kHz is the result of the influence of the heat accumulation. This effect, as well as the already discussed decrease of the plasma and particle shielding with decreasing pulse energies are probably also the reasons for the comparable ablation depths with 200kHz and 500kHz at a pulse distance of 3.75µm. At a pulse distance of 1.9µm with respectively lower pulse energies, ablations depths rise monotonously with the pulse repetition rates.

![Surface structures after laser irradiation with constant \(Q_s = 1.1J/m\)](image)

**Fig.8** Surface structures after laser irradiation with constant \(Q_s = 1.1J/m\)

(a) pulse distance 7.5µm, pulse energy 8µJ
(b) pulse distance 3.75µm, pulse energy 4µJ
(c) pulse distance 1.9µm, pulse energy 2µJ
Figure 8 shows the resulting surfaces after 250 scans with a linear energy of 1.1J/m and a pulse repetition rate of 1000kHz at three different pulse distances. The probe that was processed with a large pulse distance and correspondingly high pulse energy (Fig. 8a) has a surface with a high roughness and a typical appearance of molten and solidified material. The optimum quality was obtained with a pulse energy of 4µJ and the corresponding pulse distance of 3.75µm (Fig. 8b). With further decreasing pulse distances initial micro structures emerge locally that spread out over the entire machined surface with each additional scan (Fig. 8c).

3.4 Periodic micro structures

In several publications the observation of periodic formations on femtosecond laser processed surfaces has already been reported. These were classified according to their shape and size as ripple-, cone-, spike- or columnar structures [11-14]. Presently a generally valid explanation for the development of ripple structures is the interference between the incident laser beam with the reflected or scattered laser radiation close to the surface of the irradiated material. Figure 9 illustrates the obtained ripple formations on the work piece surface after irradiation with high repetitive femtosecond laser radiation.

The periodicity of the ripples (ca.1µm) is in the order of the irradiated laser wavelength. Their structural height is approximately 0.5µm.

Table 3 Machining parameters

<table>
<thead>
<tr>
<th>Figure</th>
<th>repetition rate [kHz]</th>
<th>pulse energy [µJ]</th>
<th>pulse distance [µm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>500</td>
<td>2</td>
<td>3.75</td>
</tr>
<tr>
<td>b</td>
<td>500</td>
<td>6</td>
<td>3.75</td>
</tr>
<tr>
<td>c</td>
<td>1000</td>
<td>2</td>
<td>3.75</td>
</tr>
<tr>
<td>d</td>
<td>1000</td>
<td>6</td>
<td>3.75</td>
</tr>
<tr>
<td>e</td>
<td>1000</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>f</td>
<td>1000</td>
<td>6</td>
<td>1.9</td>
</tr>
<tr>
<td>g</td>
<td>2000</td>
<td>2</td>
<td>1.9</td>
</tr>
<tr>
<td>h</td>
<td>2000</td>
<td>6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

At low repetition rates (500kHz) no cones occur (Fig. 11a, b). Only some singular holes can be observed in the otherwise even surface after ablation with low pulse en-
ergies (Fig. 11a). At higher repetition rates clusters of conical micro structures appear (Fig. 11c, d) that continuously expand over the processed surface during further machining. With narrow pulse distances, already after a few scans, extensive coverage of the processed surface by these micro formations has taken place. At higher pulse energies the number of cones per area decreases while their height increases (Fig. 11f, h vs. 11e, g).

4. Conclusion

First results of laser machining with high repetition ultra short laser pulses have been presented. At first a higher ablation rate with increasing pulse energy was observed. Further, at laser machining with higher repetition rates accumulation effects influence the ablation process. The higher energy input with higher repetition rates comes to a higher temperature at the machined area that decreases the ablation threshold and increases the ablation coefficient. Exceeding a critical pulse repetition rate particle shielding and plasma effects reduce the ablation rate. So laser machining with a repetition rate below these critical pulse repetition rate is more efficient than laser processing with previous laser technology. Therefore high ablation rates can be achieved up to 1.8mm³/min and as a result the high product quality, typical for femtosecond laser machining, can be obtained at industrially accepted production rates. Another effect of the high mean powers due to high repetition rates is appearance of self organized micro structures. Ripple formation occurs with a periodicity of 1µm independent of the scanning direction and crystalline orientation of the material. Other observed formations were conical microstructures. In terms of machining quality they present a drawback as they induce a high surface roughness. The influence of the various machining parameters upon these formations has yet to be investigated systematically.

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References


