High-rate laser processing of metals using high-average power ultrashort pulse lasers

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Abstract. High-rate laser processing of technical grade stainless steel by using high-PRF ultrashort pulse lasers is studied in order to gain deeper insight into material removal for micro fabrication. For this, high-average power picosecond and femtosecond lasers are utilized, providing pulses of tens of MHz repetition rate and output powers of 76 W and 32 W, respectively. For (ultra)fast raster scanning of the laser beam, the laser systems are synchronized with a high-precision galvanometer scanner or rather an in-house developed polygon scan system. The influence of the processing parameters (laser power, pulse energy, pulse repetition rate, pulse duration, and fluence) on the ablation rate, removal efficiency, and throughput are studied. In picosecond laser irradiation of stainless steel, for example, the maximum material removal rate is 5.4 mm³/min, obtained with 76 W average laser power. This is lower than the removal rate of 6.8 mm³/min by using the femtosecond laser beam and 32 W average output power. The varying removal rate is the result of the different removal efficiency of picosecond and femtosecond laser pulses, which was determined in the experimental study of 0.071 mm³/W/min and 0.22 mm³/W/min, respectively, by using identical processing parameters except the pulse duration. Finally, the machining quality of laser processed micro cavities are evaluated by means of surface roughness measurements and SEM micrograph analysis. As a result, the mid-fluence range between 0.4 J/cm² and 1.5 J/cm² is identified for ultrashort pulses as most suitable processing regime for micro fabrication with regard to removal efficiency, throughput, and machining quality.

Keywords: high-rate, high throughput, ultrashort pulse laser, micro processing, polygon

1. Introduction

Recent progress in developing high-average power ultrashort pulse lasers facilitates high-throughput machining with the potential to meet industrial needs in micro fabrication with regard to accuracy, precision efficiency and throughput. However, initial studies investigating high-PRF (pulse repetition frequency) ultrashort pulse laser processing identified heat accumulation and particle shielding as substantial ablation process influencing mechanisms [1-3]. Particle shielding effects are reported for pulses in the range of several hundred kilohertz that potentially will reduce material removal. In this time regime, the following irradiated laser pulses will be reflected, scattered and/or absorbed by ejecting particles and clusters which are produced by the preceding irradiated pulses. A further increase of the repetition rate to megahertz pulse repititions, by contrast, enhances material removal which is mainly induced by heat accumulation. In this case, the time interval between successive pulses is too short for complete cooling of the irradiated area and thus heat accumulates in a narrow subsurface area. In particular for poor heat-conducting materials, the surface temperature rises gradually inducing enlarged heat affected zones but also material melting those detrimentally affects the processing quality.

Recently, a number of systematic studies investigated the influence of pulse duration, laser fluence and pulse repetition rate on material removal in high-PRF ultrashort pulse laser micro processing [4-9]. The analysis of the results obtained identified higher removal efficiency for femtosecond pulses than for pulses in the picosecond range. In addition it is demonstrated that by optimization of the processing parameters high-quality and melt-free micro-featured devices can be produced, even with high-PRF pulses. However, the presented removal rates ranging up to 0.7 mm³/min does not fulfill industrial requirements in terms of throughput and productivity. This is mainly due to limited available maximum laser output power and can potentially be overcome by using high-average power high-PRF ultrashort pulse lasers. Thus, in a more recent approach, ten times higher material removal rates up to 6.8 mm³/min were reported, obtained with femtosecond pulses of 20 MHz repetition rate and 30 W average output power [10].

In this work, high-rate laser processing of technical grade stainless steel is studied in order to gain deeper insight into complex high-PRF material removal. By using high-average power picosecond and femtosecond lasers, material removal is evaluated with respect to efficiency, throughput and quality. It is shown that high-average power high-PRF lasers in conjunction with (ultra)fast scan technologies seem to be a promising technology to scale the productivity in micro fabrication.
2. Optimisation of material removal in ultrashort pulse laser processing

In ultrashort pulse laser micro fabrication, the achievable ablation rate, removal efficiency, throughput, and machining quality are greatly influenced by the processing parameters. A number of studies investigating ultrashort pulse laser ablation confirmed that the ablation rate increases non-linearly with higher pulse energies or rather fluence, among others [11-14]. Furthermore, it is verified by G. RACIU /KAITIS et al. [15] using picosecond laser radiation that most efficient material removal arises when the laser fluence is equal to

\[ H_{\text{opt}} = e^2 \cdot H_{\text{th}} \approx 7.4 \cdot H_{\text{th}} \]

where \( H_{\text{opt}} \) is the optimum fluence and \( H_{\text{th}} \) is the threshold fluence. As a result, increasing the pulse energy in order to enhance material removal, the maximum achievable ablation rate will only be obtained by balancing the focus diameter to the optimum spot size. To emphasize this interrelation even for femtosecond laser pulses, a theoretical analysis of the influence of both laser spot diameter and pulse energy on the ablation rate is presented in Fig. 2.1. In this figure the theoretically achievable volume ablation rate \( V_{\text{SP}} \) is computed for stainless steel by using Equation 2.2. The effective penetration depth \( d_{\text{eff}} = 15 \, \mu m \), focus radius \( w_o = 11 \, \mu m \) and ablation threshold \( H_{\text{th}} = 0.1 \, J/cm^2 \) were taken into calculation. These calculation input values were determined for stainless steel in our previous experimental studies [9].

\[ V_{\text{SP}} = \frac{d_{\text{eff}} \pi w_o^2 \ln^2 \left( \frac{H_o}{H_{\text{th}}} \right)}{4} \]

In Fig. 2.1 it can be seen, for example, that a pulse energy of 1.5 µJ will be the optimum for femtosecond laser pulses of 22 µm focus spot diameter. By irradiating pulses of higher energy at same spot diameter, the volume ablation rate increases, but most efficient material removal only takes place when the fluence is at optimum level. For stainless steel, the optimum fluence is determined of 0.74 J/cm², as indicated in the figures. This is about a factor of 7.4 above the ablation threshold which is in accordance with Equation 2.1.

Fig. 2.2 plots the calculated volume ablation rate as a function of the fluence; the focus diameter was varied in the range between 15 µm and 50 µm. It can be seen for pulses of fixed diameter, on the one hand, that the volume ablation rate increases with higher fluence. On the other hand, for pulses at fixed fluence, the ablation rate increases with larger diameter. In both cases, whether increasing fluence or larger diameters, a higher amount of laser energy irradiates the substrate causing higher material removal. As another assessment criterion, the efficiency of material removal was evaluated in order to identify the optimum processing regime. For this, the calculated volume ablation rate values were divided by the pulse energy. The results obtained are presented in Fig. 2.2 by plotting the removal efficiency versus fluence.

The plot of the removal efficiency in Fig. 2.2 confirms that material removal is most efficient by irradiating pulses at 0.74 J/cm² fluence as already mentioned above in Fig. 2.1. Using this optimum fluence, the maximum achievable material removal per laser energy expenditure is about 4.1 µm³/µJ for stainless steel. In addition, it is identified that maximum material removal can be achieved independently from the applied focus diameter or rather pulse energy, which varied depending on the focus spot size. From this finding it can be supposed that the maximum material removal rate can be achieved by different approaches. As long as the fluence is optimum, a high quantity of sharply focused low-energy laser pulses, as the first processing regime, or as second regime, a lower quantity of high-energy laser pulses of wider focus diameter will bring identical removal rates.
This functional relation is analysed more in detail in Fig. 2.3. Therein the removal rate MRR is calculated for varied processing conditions according to Equation 2.3. In this equation \( V_{SP} \) is volume ablation rate and \( f_R \) is the repetition rate; the time interval is one minute.

\[
MRR = V_{SP} \cdot f_R \cdot 60s
\]  

By varying the focus diameter, the computed removal rates are shown in Fig. 2.3 as a function of the repetition rate and, for example, by taking into account a femtosecond laser system of 30 W average laser output power. It is shown that the maximum removal rate of 7.32 mm³/min can be obtained with different parameter sets. According to this, the most efficient processing points are addressed with their repetition rate, the corresponding pulse energy, and the focus diameter. However, in each case the maximum removal rate arises at the optimum fluence of 0.74 J/cm².

![Graph](image)

**Table 2.3.** The removal rate theoretically calculated as a function of the repetition rate, the focus diameter is varied in the range between 15 µm and 100 µm, a femtosecond laser with 30 W average output powers is considered.

According to **NEUENSCHWANDER et al.** [6, 16], for a given average laser power the maximum ablation rate can be obtained at an optimum repetition rate, or rather, the removal rate shows a maximum for optimum applied fluence. This functional interrelation is given in Equation 2.4, where \( V \) is the removable material volume per time interval, \( P_{av} \) is the average laser power, \( \delta \) is the effective penetration depth, and \( H_{th} \) is the ablation threshold.

\[
\frac{V}{P_{av}}_{\text{max}} = \frac{2}{e^2} \cdot \frac{\delta}{H_{th}}
\]  

By taking into account the effective penetration depth of 15 nm, the removal efficiency of stainless steel calculates to 0.244 mm³/W·min. As a result, irradiating 30 W average laser powers to stainless steel, a material volume of 7.32 mm³ can be theoretically removed per minute. This quantity has been already accounted in Fig. 2.3.

### 3. Experimental details and analysis methods

Two different high average power high-PRF ultrashort pulse laser systems were investigated, a femtosecond laser supplying a maximum laser power of 31.7 W and maximum repetition rate of 19.3 MHz, and a picosecond laser with a maximum average power of 70.0 W and 20 MHz pulse repetition rate.

The picosecond laser was utilized with an in-house developed polygon mirror system, allowing two-dimensional raster scanning of the laser beam with maximum scan speeds of 880 m/s in polygon scan direction. With the adapted f-theta lens, the picosecond laser beam was focused onto the material surface to a spot size of 44 µm. Using this ultrafast polygon scan system, deflection of the picosecond laser beam was sufficiently high to reach the proposed optimum lateral pulse-to-pulse spacing of about half of focus radius [5, 17] even in case of megahertz repetitive pulses. According to Equation 3.1, where \( v_S \) is the scan speed, \( d_p \) is the pulse-to-pulse spacing in scan direction, and \( f_R \) is the repetition rate, a scan speed of 200 m/s was required to get 10 µm pulse-to-pulse spacing at 20 MHz.

\[
v_S = d_p \cdot f_R
\]  

The femtosecond laser beam was focused using a 255 mm f-theta lens in conjunction with a high-performance galvanometer scanner (**intelliSCANde®**, Scanlab AG) to a focus spot diameter of 22 µm. The maximum scan speed of the galvanometer scanner setup was 17 m/s. As a result, the optimum pulse-to-pulse spacing of about 5 µm was only achievable for pulses of 3.4 MHz repetition rate or lower.

### Table 3.1. Summary of the parameters investigated in this study.

<table>
<thead>
<tr>
<th>sci-series (Active Fiber Systems AG)</th>
<th>PX series (EdgeWave GmbH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>wavelength ( \lambda ) [nm]</td>
<td>1030 1064</td>
</tr>
<tr>
<td>repetition rate ( f_R ) [MHz]</td>
<td>19.3 20</td>
</tr>
<tr>
<td>av. laser power ( P_{av} ) [W]</td>
<td>31.7 76</td>
</tr>
<tr>
<td>pulse energy ( Q_{SP} ) [µJ]</td>
<td>30.5 75</td>
</tr>
<tr>
<td>pulse duration ( \tau_w ) [ps] (sech²)</td>
<td>0.35 10</td>
</tr>
<tr>
<td>focus spot diameter ( w_0 ) [µm]</td>
<td>22.3 44</td>
</tr>
<tr>
<td>fluence ( H_{f} ) [J/cm²]</td>
<td>16.0 9.9</td>
</tr>
<tr>
<td>scan speed ( v_S ) [m/s]</td>
<td>17 200</td>
</tr>
</tbody>
</table>

By studying femtosecond pulses of higher repetition rate, the pulse-to-pulse spacing reduced, for example, to
3.5 µm or rather 0.9 µm for pulses of 4.83 MHz or 19.3 MHz, respectively. The laser parameters investigated in this study are summarized in Table 3.1.

For empirical estimation of the optimum processing parameters, cavities of standardized geometry were produced by raster scanning the focused laser beam. Laser raster scanning implies a network of overlapping parallel laser processed lines of constant hatch distance \( d_H \), as shown in Fig. 3.1.

![Sketch of the raster-scanning method](image)

**Fig. 3.1.** Sketch of the raster-scanning method, where \( d_F \) is lateral pulse-to-pulse spacing, \( d_H \) is hatch distance, and \( v_S \) is scan speed.

With increasing number of raster scan passes \( n_S \) processed on the sample surface, the cavity depth \( d_C \) increased. The cavity depths were measured using a confocal point sensor (\( \mu \)scan CF, nanoFocus AG) and, according to Equation 3.2, from this value the experimentally achievable volume ablation rate \( V_{SP} \) was calculated.

\[
V_{SP} = \frac{d_F \cdot d_H \cdot d_C}{n_S}
\]

Finally, the machining quality was evaluated by means of the average surface roughness \( S_r \) of the laser processed cavity bottom surfaces. The roughness measurements were carried out using the confovis 3D measuring assembly ConfoSurf CLV150.

### 4. Results and discussion

#### 4.1 Ablation rate, throughput and efficiency

High-PRF ultrashort pulse laser ablation of technical grade stainless steel was investigated on the basis of cavity depths. Therefore, rectangular cavities with the dimension 7.0 x 0.5 mm² in length and width were produced using both the femtosecond and picosecond laser.

The volume ablation rates obtained with the femtosecond laser are plotted as a function of the fluence in Fig. 4.1. Furthermore, in order to evaluate the influence of the temporal pulse-to-pulse distance on material ablation, the repetition rate was varied in the range between 508 kHz and 4.38 MHz. The cavities were produced with 30 scan passes and constant lateral pulse-
to-pulse spacing which was 5 µm in \( X \)- and \( Y \)- direction. As an exception, the pulse spacing reduced a little in scan direction to 4.0 µm and 3.5 µm at the higher repetition rates of 3.86 MHz and 4.83 MHz which was due to the limited scan speed of the galvanomer scanner of 17 m/s.

Fig. 4.1 points out that the volume ablation rate increased non-linearly with the fluence. The experimental data obtained in the fluence range between 0.4 J/cm² and 6.0 J/cm² are in good correlation to the modeled ablation curve, calculated according to Equation 2.2. In addition, it can be seen in Fig. 4.1 that material removal is not or, in case of 4.8 MHz repetition rate, only marginally influenced by the repetition rate.

![Graph](image)

**Fig. 4.1.** The experimentally determined volume ablation rate using the femtosecond laser with 22 µm focus diameter and 31.7 W maximum average output power, the repetition rate was varied in the range between 508 kHz and 4.83 MHz.

This finding agrees with the results presented by NEUENSCHWANDER et al. [18] who concluded for high-PRF picosecond laser radiation that ablation of stainless steel is not or only weakly affected by plasma/particle shielding and heat accumulation. This was in particular by irradiating pulses at optimum fluence and lateral pulse-to-pulse spacing of half of spot radius. However, our previous studies reveal that particle shielding losses (as detected in high-PRF femtosecond laser processing of stainless steel) will be overbalanced by heat accumulative effects [3, 5, 9]. We observed a significant increase of the ablation rate by irradiating pulses at 1 MHz repetition rate and wider lateral spacing, compared to the ablation results obtained with either lower repetition rates or smaller spacing or both [19]. From this it can be suggested that the role of the repetition rate or rather the temporal pulse-to-pulse distance in ultrashort pulse laser ablation is not fully clear and further research seems to be needed in this issue.

Fig. 4.2 plots the material removal rate versus the fluence. The material removal rates are calculated in accordance with Equation 2.4 by taking into account the experimentally volume ablation rates given in Fig. 4.1 and the pulse repetition rates. In addition, the material...
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removal rates obtained in a previous work by using femtosecond pulses at 200 kHz repetition rate are included in the plot. In spite of the fact that the volume ablation rate was almost identical for pulses of similar fluence, see Fig. 4.1, in Fig. 4.2 the lowest investigated pulse repetition rate of 200 kHz yields the smallest material removal rate. This is the result of the lowest number of incident laser pulses per time interval, and the removal rate increases with higher pulse repetition rates. For a fixed repetition rate, however, it can be seen that higher material removal was achieved with higher fluence.

![Material removal rate vs. Fluence](image)

**Fig. 4.2.** The experimentally determined material removal rate using the femtosecond laser with 22 µm focus diameter and 31.7 W maximum average output power, the repetition rate was varied in the range between 200 kHz and 4.83 MHz.

In Fig. 4.2 the highest removal rate of 4.36 mm³/min can be seen, obtained with pulses of 3.4 J/cm² fluence and 4.83 MHz repetition rate. With regard to Section 2 it becomes obvious, on the one hand, that this fluence is not in the optimum range and thus the achieved removal rate is less than the theoretically estimated value of 7.32 mm³/min. On the other hand, the poor quality of the cavity bottoms produced with these high-fluence pulses does not fulfill the requirements in micro fabrication for industrial applications. This can be observed, for example, in Fig. 4.3 c) showing a cone-like protrusion covered rough cavity bottom, produced with pulses of 3.21 J/cm² fluence and 3.22 MHz repetition rate. In contrast, cavities with smooth and regularly ripple textured bottoms were machined by irradiating pulses of the same repetition rate but lower fluence, such as shown in Fig. 4.3 a) and b) for pulses of 0.49 J/cm² and 1.0 J/cm² fluence, respectively.

Based on these experimental findings, three different processing regimes are indicated in Fig. 4.2 with regard to their achievable processing speed and quality. In the low-fluence regime with fluence lower than 0.4 J/cm², high-quality machining outcomes can be produced but the processing speed is comparably low. In the mid-fluence regime as the second regime where the fluence is in the range between 0.4 J/cm² and 1.5 J/cm², the laser process is highly efficient, providing maximum processing throughput and good machining qualities. Laser processing in the high-fluence regime with fluence higher than 1.5 J/cm² will bring the highest removal rate per pulse. As major disadvantage of the third regime, there is an unsatisfactory level of machining quality, removal efficiency and throughput, as presented in Fig. 4.3 and Fig. 4.4.

![SEM micrographs](image)

**Fig. 4.3.** SEM micrographs showing the bottom surface of laser processed cavities using the femtosecond laser at 3.22 MHz and fluence as follows: a) 0.49 J/cm², b) 1.0 J/cm², c) 3.21 J/cm².

Fig. 4.4 evaluates the removal efficiency depending on the fluence, the repetition rate is varied. The removal rates were calculated by dividing the experimentally determined material removal from Fig. 4.2 by the irradiated average laser power. Nevertheless, high-fluence pulses yield the highest ablation rate and thus material removal rate but the highest removal efficiency can be observed for pulses in the mid-fluence range. For pulses of higher fluence, by contrast, the removal efficiency reduced. From this it can be supposed that only a certain amount of laser energy will be consumed for material removal which might be due to the fact that the laser ablated volume is influenced by energy penetration into the bulk. In addition, by keeping in mind that the
Ablation rate increases non-linearly with higher fluence, it can be suggested for high-fluence pulses that higher amounts of laser energy will most likely deposited as heat. This, in turn, lowers the process efficiency and will potentially have detrimental effects on the machining quality.

For low-fluence pulses it can be pointed out that steel ablation will take place as long as the fluence is above the ablation threshold. In Fig. 4.4 the low-fluence range is highlighted in red colour indicating that material ablation is inefficient. This is potential induced by the limited energy penetration into the depth which is mainly driven in the low-fluence regime by optical penetration instead of ballistic electron movement. As a result, the irradiated energy will be deposited in a narrow sub-surface volume which is considerably smaller than that volume which theoretically can be vaporized by considering the quantity of impinging laser energy.

Most-efficient material removal arises in the mid-fluence range, as indicated in green in Fig. 4.4. The theoretically achievable removal efficiency of 0.244 mm³/W/min is experimentally confirmed by pulses of the lower repetition rate of 200 kHz. By contrast, using pulses between 508 kHz and 3.86 MHz, the removal efficiency maximum was found to be 0.33 mm³/W/min. This is considerably higher than the modelled removal efficiency. As a reason it can be supposed that heat accumulative effects, potentially occurring in high-PRF ultrashort pulse laser processing, enhances the efficiency of material removal. Furthermore, Fig. 4.4 identifies for pulses of 4.8 MHz repetition rate that their removal efficiency reduces to 0.22 mm³/W/min, which is below the theoretical removal efficiency. This might be affected by plasma/particle shielding. Overall, the results obtained by studying the removal efficiency suggest that ultrashort pulse laser processing in the mid-fluence range seems to be the optimum for micro fabrication.

There is also a dependence of machining throughput on fluence and repetition rate, both associated by average laser power. In Fig. 4.5, the experimentally achieved volume ablation rate as well as the material removal rate is plotted as a function of the repetition rate. The plot illustrates that the ablation rate decreases significantly by using pulses of higher repetition rate. This is due to the fact that the pulse energy and thus the fluence decrease with increasing repetition rate as a result of the limited available maximum average laser output power.

Furthermore, as a general trend, a higher volume ablation rate was achieved with the femtosecond laser of 31.7 W average laser power although more than twice higher laser power or rather laser energy at similar repetition rates were supplied by the picosecond laser. Explanations therefore can be found in a previous study, presenting higher material removal for femtosecond laser radiation than for picosecond laser beams [20]. It was reported that the effective energy penetration depth in steel has almost quadruplet by using femtosecond pulses compared to picosecond pulses of similar beam properties. As has been already argued above, energy penetration has a great effect on the volume ablation rate, see Equation 2.2.

In addition, Fig. 4.5 shows a greater material removal rate for femtosecond laser pulses compared to picosecond pulses at similar repetition rate. For the investigated femtosecond laser, the highest material removal rate was 6.81 mm³/min, achieved with pulses of 19.3 MHz repetition rate, 0.85 J/cm² fluence and 31.7 W laser output power. In this case the fluence was in the optimum range, enabling most-efficient material removal. This becomes also obvious by dividing the experimentally removal rate by the applied laser power. As a result, the removal efficiency calculates to 0.21 mm³/W/min for pulses of 19.3 MHz, which is lower than the theoretical
removal efficiency of 0.244 mm³/W/min or rather the data given in Fig. 4.4 where the maximum efficiency was 0.33 mm³/W/min. It should be mentioned here that the lateral pulse spacing was smaller than 1 µm at this high repetition rate, which was due to the limited scan speed of the galvanometer scanner (17 m/s). From this it can be supposed that particle shielding will diminish the removal efficiency by using high-PRF pulses in the range of 20 MHz. The next following laser pulses will strongly interact with the plume of plasma and/or ablated particles initiated by previous pulse irradiations.

The maximum removal rate of the high-PRF picosecond laser beam was 5.4 mm³/min, obtained with pulses of 0.5 J/cm² fluence, 20 MHz repetition rate and maximum laser output power of 76 W. From this removal rate value the experimental removal efficiency was estimated of 0.071 mm³/W/min. This is slightly less than the theoretical removal efficiency of 0.081 mm³/W/min, calculated according to Equation 2.2 by taking into account 0.1 J/cm² threshold fluence and, in comparison to femtosecond pulses, a significant lower effective energy penetration depth of 5 µm.

Particle shielding, on the one hand, may cause the difference occurred between the experimental and theoretical removal efficiency although wider pulse spacing of 10 µm was used here. This spacing was achieved between high-PRF pulses of 20 MHz by using the polygon scanner and scan speed of 200 m/s. On the other hand, using picosecond pulses of 20 MHz, the fluence was not in the optimum range. This might be contributed to the fact that the removal efficiency reduced. A maximum fluence of 0.5 J/cm² was available at 20 MHz even for 76 W average laser powers because of the focus diameter enlarged to be 44 µm by using the polygon scanner setup. However, the above results emphasize the previous statement that femtosecond laser pulses are more efficient for stainless steel removal than picosecond pulses in the same parameter range.

In Fig. 4.6, SEM micrographs of cavity bottoms produced using high average power picosecond and femtosecond lasers are placed opposite to each other. It is worth noting that pulse energy and fluence varied for the cavities those were made with almost identical repetition rates. This variance was due to different available maximum laser power and focus spot diameter of both laser systems to be compared. For each micrograph, the processing parameters as well as the average roughness Sₐ evaluated over the 3D surface are presented in Fig. 4.6.

In general, the cavities produced with higher pulse energy or rather fluence show strongly rugged coral-like micro featured bottoms. While picosecond laser ablation initiated more or less cone-like protruded surfaces, the femtosecond laser made cavities appeared fissured including a high number of micro holes. For the pulses of higher fluence, the surface roughness was measured to be Sₐ = 2.1...4.9 µm for the femtosecond and Sₐ = 1.9...3.3 µm for the picosecond laser beam, respectively. In case of lower fluence, considerably smoother surfaces were produced. The lowest roughness was achieved with pulses in the optimum fluence range, measured of Sₐ < 0.6 µm for picosecond and Sₐ < 0.4 µm for femtosecond pulses.

![Fig. 4.6. SEM micrographs showing the surface bottom of laser produced cavities as obtained by using high average power femtosecond (left) and picosecond (right) laser beams, the maximum available average laser power was irradiated, the repetition rate was varied, the operating pulse energy and fluence as well as the average bottom roughness are presented.](image)

It is noteworthy that the smoothest cavity bottom was achieved with femtosecond pulses of 19.3 MHz although the pulse spacing was less than 1 µm. This is in contrast to our results obtained in previous studies, where rough
cone-like protruded surfaces were observed for femtosecond pulses of 1 J/cm² fluence, 1 MHz repetition rate, and 1 μm pulse spacing [3, 21]. High-quality smooth surfaces were obtained in this case by enlarging the pulse spacing in the range of half focus spot radius.

From the results obtained in this study it can be concluded that ultrashort pulse laser processing in the mid-fluence regime will facilitate the best machining outcomes with regard to their efficiency, throughput and quality. However, in high-rate laser processing using ultrashort pulse lasers with high average output power, (ultra)fast movement of the laser beam is essential to achieve the required lateral pulse-to-pulse spacing even for pulses of several MHz repetition rate. For this, polygon scan systems seem to be a promising technology, providing sufficiently high scan speeds in the range of hundreds to thousands of meters per second. This was already successfully demonstrated in a previous work investigating an in-house developed two-axis polygon scanner [22].

Summary

High-rate laser processing of stainless steel using high-average power ultrashort pulse lasers in conjunction with (ultra)fast scan systems was studied. Initially, a theoretical analysis of material ablation identified the mid-fluence range as optimum process regime with regard to ablation rate and throughput. It was demonstrated for femtosecond laser pulses that most efficient material removal will take place when the fluence is 7.4 times above the ablation threshold. For this, the maximum removal efficiency was computed of 0.244 mm³/W/min and therefore, by taking into account 30 W average laser powers, a maximum removal rate of 7.32 mm³/min was calculated. It was shown that this maximum removal rate can be obtained with different parameter sets by balancing the focus diameter and the pulse energy to the optimum fluence of 0.74 J/cm².

In the experimental analysis, material removal was studied using high average power high-PRF ultrashort pulse lasers, a femtosecond laser with 31.7 W and a picosecond laser with 76 W average output power. It was found that both, volume removal per laser pulse (defined as volume ablation rate) and removable material volume per time increment (defined as material removal rate) increases with increasing fluence. Thereby no significant influencing effects of the repetition rate on the ablation rate were observed. However, it cannot be ruled out, therefore, that heat accumulation and particle shielding balancing each other in the studied range between 508 kHz and 4.83 MHz pulse repetitions. This hypothesis is supported by the analysis of the removal efficiency. While for high-PRF pulses in the range between 508 kHz and 3.8 MHz the removal efficiency enhanced to 0.33 mm³/W/min, theoretically the removal efficiency was determined of 0.244 mm³/W/min. By irradiating pulses of higher repetition rate the removal efficiency decreased to 0.22 mm³/W/min and 0.21 mm³/W/min, as obtained with pulses of 4.83 MHz and 9.3 MHz, respectively.

The maximum removal rate using the femtosecond laser and 31.7 W average powers was 6.81 mm³/min. This was greater than 5.4 mm³/min maximum removal rate as obtained with the picosecond laser by emitting more than twice higher laser power of 76 W. As main reason for this, the considerably lower removal efficiency of picosecond pulses was identified, which was estimated of 0.071 mm³/W/min in the experimental study.

Finally, the processing quality was evaluated by SEM photographing and roughness measurements on the laser processed cavity bottoms. As a general trend it was found that the bottom roughness reduced with pulses of lower fluence. The smoothest cavity bottoms with average surface roughness of \( S_a < 0.6 \) μm for the picosecond or \( S_a < 0.4 \) μm for the femtosecond laser were produced with pulses in the mid-fluence range.

In conclusion, ultrashort pulse laser processing in the mid-fluence range will facilitate the best machining outcomes with regard to their efficiency, throughput and quality. Moreover, high-rate laser processing using high average power high-PRF ultrashort pulse lasers utilized in conjunction with (ultra)fast laser beam movement systems can be supposed as key enabling technology with the potential to substitute standard manufacturing technologies in modern micro fabrication.

Acknowledgments

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