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Laser surface structuring with 100 W of average power and sub-ps pulses

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High throughput still represents a key factor for industrial use of ultrashort pulses in the field of surface structuring. Reliable systems with average powers up to 100 W are today available. It has already been proved that metals, especially steel having a low threshold fluence, can be machined with excellent surface quality at average powers of more than 40 W and a spot radius of about 25 μm, if a polygon line scanner, offering fast scanning speeds, is used. A further scale-up into the 100 W regime should be possible for metals showing a threshold fluence of about 0.2 J/cm^2 or higher. But, it will lead to problems with heat accumulation in the case of steel and a straight forward scale-up is not possible. In order to keep a good surface quality, the machining strategy has to be adapted. A maximum flexibility can be obtained with an "interlaced" mode by using very high marking speeds of several 100 m/s and repetition rates of several tenths of MHz. As this is at the edge of today available technologies, alternative strategies are additionally investigated. Enlarging the spot size represents the most simple approach to reduce the heat accumulation in the case of steel but also multispots represent an attractive alternative. © *2016 Laser Institute of America.*
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Key words: laser micromachining with ultra-short pulses, high throughput surface texturing, power scale-up

I. INTRODUCTION

Ultrashort laser pulses have shown their applicability for high quality laser micromachining of metals, semiconductors, and insulators in manifold applications. However, to really enter into the large field of industrial applications, the demand of high throughput still represents one of the key factors. It was shown, especially for metals, that the efficiency of the ablation process can be optimized, i.e., that there exists a maximum specific removal rate (removal rate per average power) at a certain optimum fluence.[1,2] This maximum specific removal rate depends on the pulse duration[3–6] as well, whereas shorter pulses lead to higher values. In the case of metals, the threshold fluence typically ranges from 0.05 to 0.5 J/cm^2. Working at this optimum point demands only moderate fluences. Thus to work at high average powers high repetition rates are needed. In Ref. 7, it has been shown that minimum surface roughness is achieved with a pitch, distance from pulse to pulse, of half to one spot radius, i.e., a spatial overlap of 50%–75%. Hence, high repetition rates automatically demand high marking speeds. These high scan speeds are, e.g., offered by fast rotating cylinders which can either be combined with additional acousto-optic deflectors[8] or be completely synchronized with the laser system.[9,10] A more flexible approach are polygon line scanners offering marking speeds of 100 m/s and higher as well as the possibility of a synchronization with the laser system.[11] Results with a 50 W ps laser-system are reported in Refs. 12 and 13 where it is shown that neither heat accumulation nor plasma-shielding significantly influences the removal rate and machining quality for different steel grades up to an average power of 42 W going with maximum repetition rates up to 6.8 MHz. However, it has to be clarified to what average power the ablation process is scalable, i.e., the specific removal rate does not change and the machining quality can be maintained when working at the optimum point with a pitch between half and one spot radius. In a next step, the regime from 50 to 100 W average power with a sub-ps laser system will be investigated.

II. THEORY

In case of a Gaussian beam, the maximum specific removal rate and the corresponding peak fluence read[14]

$$\frac{\dot{V}_{\max}}{P_{\mathrm{av}}} = 2 \cdot \frac{\delta}{\phi_{0,\mathrm{pot}}} \text{ and } \phi_{0,\mathrm{pot}} = e^2 \cdot \phi_{\mathrm{th}}, \tag{1}$$

with ϕ_{th} being the threshold fluence and δ being the energy penetration depth. For a straight line, the marking speed v will then depend on the spot radius w_0, the overlap o, and the average power P_{av} or the optimum repetition f_{opt}

$$v = \frac{4}{\pi \cdot e^2} \cdot \frac{(1-o) \cdot P_{\mathrm{av}}}{w_0 \cdot \phi_{\mathrm{th}}} = 2 \cdot w_0 \cdot (1-o) \cdot f_{\mathrm{opt}}. \tag{2}$$

For example, for spot radius of $w_0 = 25\ \mu$m, an overlap of 75%, and an average power of 50 W, the desired marking speed would be more than 150 m/s for steel 1.4301, AISI 304 in U.S., ($\phi_{th} \approx 0.055$ J/cm^2) and about 29 m/s for copper ($\phi_{th} \approx 0.3$ J/cm^2), respectively. Especially for steel, the desired marking speeds exceed 100 m/s already for a few tenths of W average power. On the other hand, with polygon line scanners marking speeds up to a few 100 m/s (Ref. 15) or even up to 1000 m/s and more[16] are accessible, in principal.

However, a limiting factor would be single pulse switching, e.g., for the example of steel 1.4301 mentioned before the optimum repetition rate at 100 W average power would be around 25 MHz. It would be a big challenge to switch single pulses at this high repetition rate with an acousto- or electro-optic modulator. Typically, one has to accept some pre and post pulses limiting the minimum achievable structure size but not the whole structuring application.

Another effect to consider is heat accumulation. For steel 1.4301 and 6 ps pulses at 1030 nm wavelength 35%–40% of the pulse energy rests in the material[17] whereas for aluminum and 60 fs single pulses at 800 nm wavelength, the stored energy can increase up to 70%.[18] This deposited energy will lead to heat accumulation and can therefore influence the machining quality. For example, for steel 1.4301 it is reported[17] that a bumpy surface covered with cavities will appear if the pitch go below a certain value. As this value depends on the offset temperature of the target, it is assumed that these cavities are formed if the surface temperature exceeds a critical value. By comparing experimental data with numerical simulations, it was found that the critical temperature raise just before the next pulse strikes on the surface amounts about 610 °C. For an instantaneous Gaussian shaped heat source of energy $\eta \cdot E_p$ with center at $(x_c, y_c, 0)$, the temperature rise inside an infinite homogeneous solid can be expressed by an analytical expression $T^{sp}_{(x_c,y_c)}(x, y, z, t)$.[17] By a corresponding summation of single pulse solutions, the temperature distribution for a specific situation like a pulsed Gaussian beam moving with velocity v along a straight line can be calculated by

$$T(x, y, z, t) = \sum_{i=1}^{N} T^{sp}_{(x_{c_i}, Y_{c_i})}(x, y, z, t_i). \quad (3)$$

The resulting temperature distribution can be used as a first approximation for the heat accumulation.

Plasma and particle shielding is discussed in detail in Ref. 19. Due to particle shielding, the transmissions through the particle plume produced by the ablation process are reduced to minimum values of 60% for aluminum, 30% for steel, and 50% for copper. But these values have been achieved with very high fluences of 17 J/cm^2 for aluminum and 18 J/cm^2 for copper and steel. For the moderate peak fluences used at the optimum point of about 0.4 J/cm^2 for steel and 2.2 J/cm^2 for copper, the transmissions are much higher and particle shielding should not cause any problems. This has been confirmed up to 42 W of average power in Ref. 13.

III. EXPERIMENTAL SETUP

A. Galvo scanner

For low repetition rates up to 2 MHz, a standard intelliSCAN$_{de}$14 Galvo scanner was used. The scanner is fully synchronized to the laser pulse train representing the master clock.[7] The used objective had a focal length of 160 mm at 1064 or 1030 nm wavelength resulting in a spot radius of about 16 μm.

B. Polygon scanner

For higher repetition rates, the experiments were performed with the LSE-170 polygon line scanner presented in Refs. 11–13. The marking speeds ranged from 25 up to 100 m/s and the beam was focused via a telecentric objective of 190 mm focal length formed by curved mirrors resulting in a spot radius of about 29 μm. For new experiments, this setup was extended with an automatic z-axis and the beam path was improved resulting in a tighter spot with a radius of $w_0 = 22.6$ μm. This improved setup is shown in Fig. 1.

C. Laser source

The former scale-up experiments to 42 W average power were performed with a FUEGO 50 W ps-system at the fundamental wavelength of 1064 nm. The pulse duration amounted 10 ps, the beam quality was $M^2 < 1.3$, and the maximum repetition rate amounted 8.2 MHz. Single pulse switching was possible up to about 2.7 MHz, for higher repetition rates pre and post pulses appeared.

For the scale up to 100 W, a new sub-ps system is developed. In the current state, the output power before the pulse on demand option exceeds 120 W at a pulse duration of about 850 fs and a beam quality $M^2 < 1.5$. The prototype was setup in the lab of the project partner LUMENTUM. Unfortunately, a delay in the delivery of mechanical parts made it impossible to deliver the industry-oriented prototype, shown in Fig. 2, until the deadline for the present article. Therefore, maximum repetition rate and limit of single pulse switching are not exactly known at this moment and further improvements are still expected.

Further as a preparation for the power scaling experiments to 100 W simulations according to Eq. (3) will be presented for different machining strategies. Experiments with the existing laser system help to support and confirm a few of these results.

IV. EXPERIMENTAL RESULTS

A. Influence of the pulse energy

To deduce the influence of the pulse energy or the fluence squares of 1.6 mm side length were machined with 196 slices, at a repetition rate of 200 kHz and a pitch of 8 μm for steel 1.4301 and copper. The peak fluence ϕ_0 was raised from a value near the threshold up to about 65 times $\phi_{th.}$ The ablated volume was deduced by measuring the depth of the squares. Dividing this value by the average power and the theoretical machining time leads to the specific removal rate. The surface quality was evaluated by taking microscopic images.

The results for steel are summarized in Fig. 3. For a fluence near the optimum point, the surface quality is excellent (a) whereas a doubling of the fluence already leads to a

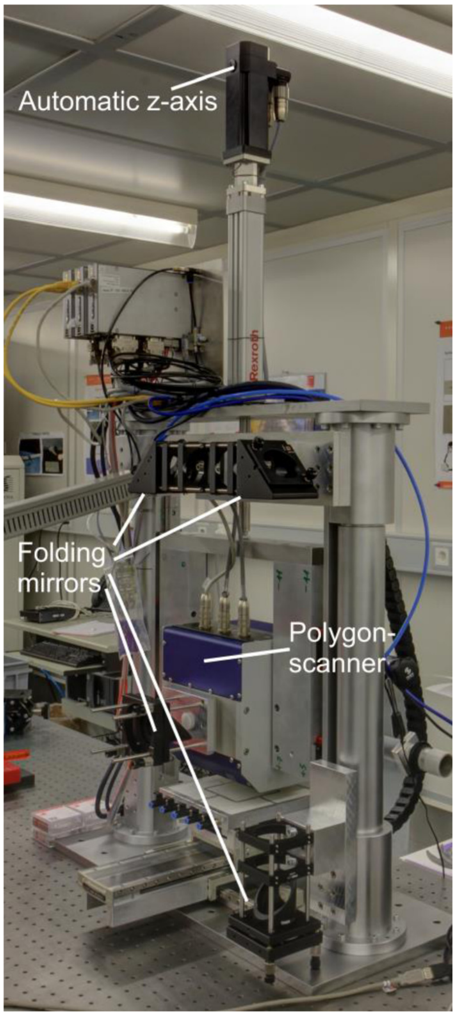

FIG. 1. Setup of the polygon line scanner mounted on an automatic z-axis. The beam is guided via four folding mirrors into the scanner.

strong formation of cavities (b) which will cover the whole surface for higher fluences as shown in (c). The formation of these cavities reduces the surface quality and the specific removal rate as well. Therefore, it does not exactly follow the model presented in Refs. 1, 2, and 14 for fluences slightly above the optimum value where the cavity formation starts. Simulations were performed for a pulsed beam moving along a straight line with 40% of the pulse energy assumed to be converted to heat. The corresponding maximum temperature

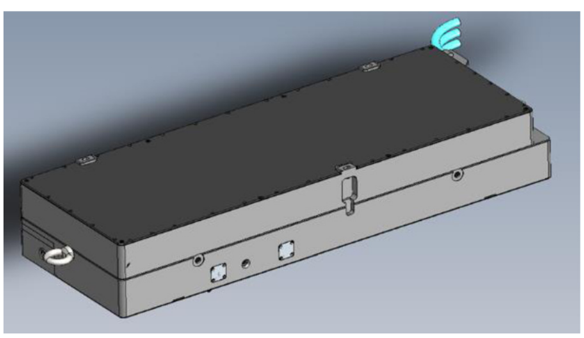

FIG. 2. Computer aided design (CAD) picture of the industry-oriented prototype of the new laser system.

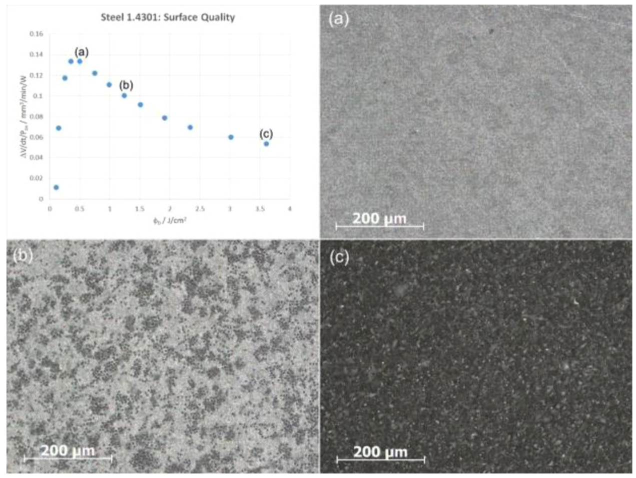

FIG. 3. Specific removal rated of steel 1.4301 (AISI 304) as a function of the peak fluence (top left). At the fluences indicated with (a)–(c) a microscope image of the surface is additionally shown.

just before the next pulse strikes on the surface amounts 140 °C for (a), 350 °C for (b), and 1075 °C for (c). As cavities already appear for fluences lower than in (b), its formation is not only caused by heat accumulation but also by too high fluences, i.e., for steel the applied fluence should not exceed the optimum value when a good surface quality has to be maintained.

The results for copper are summarized in Fig. 4 where again an excellent surface quality is observed at the optimum point (a). In contrast to steel, some kind of a waviness in horizontal and vertical direction can be observed whereas its period is smaller in the vertical direction. It has to be clarified if this difference in the waviness is caused by the scanning direction of the Galvo scanner which was horizontal for these experiments. This waviness is more pronounced for a four times higher fluence (b) and at the maximum fluence of about eight times the optimum first structures like cavities appear near the border of the squares (c). The deduced removal rates generally follow the model function[1,2,14] up to the highest applied fluence. Here, the calculated maximum

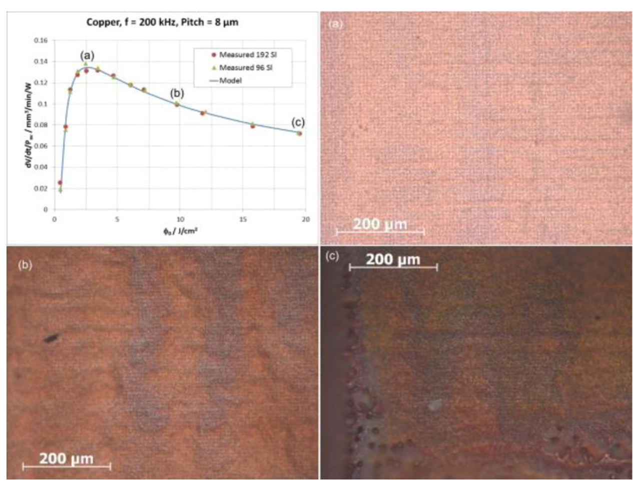

FIG. 4. Specific removal rated of copper DHP as a function of the peak fluence (top left). At the fluences indicated with (a)–(c) a microscope image of the surface is additionally shown.

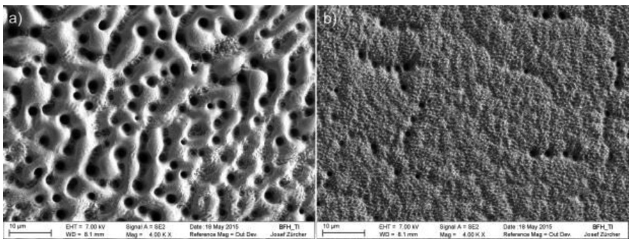

FIG. 5. Surfaces on steel 1.4301 obtained at a peak fluence of 0.55 J/cm^2 and a repetition rate of 8.2 MHz with a pitch of 3.1 μm (a) and 12.2 μm (b).

temperatures are 8.2 °C, 31.4 °C, and 62.7 °C, respectively, assuming 40% of the pulse energy is converted to heat.

B. Scale-up

To verify the assumption of the existence of a critical temperature raise of 610 °C (Ref. 17), similar experiments by varying the pitch were performed with the polygon line scanner and the existing laser system. As the spot size was reduced compared to the former experiments, the peak fluence at the highest repetition rate of 8.2 MHz and the maximum output power is 0.55 J/cm^2. This value is about 35% above the optimum value of 0.4 J/cm^2. For these experiments, the pitch was reduced from 12.2 μm down to 3.05 μm by reducing the polygon speed. The number of slices was adapted from 120 slices at a pitch of 12.2 μm to 30 slices at a pitch of 3.1 μm. The corresponding scanning electron microscope (SEM) pictures are shown in Fig. 5. For the small pitch, the surface temperature exceeds the melting temperature and strong cavity formation is observed [Fig. 5(a)]. Even for the high pitch cavity formation had already started. For this situation, the simulation reveals a temperature raise of about 780 °C thus the existence of a critical temperature raise is confirmed and its value is assumed to be between 600 °C and 800 °C.

To investigate the scale-up process to 100 W, the corresponding temperature raise was calculated according to Ref. 17. The peak fluence was set to its optimum value, and the pitch was fixed at 12.2 μm (about half of a spot radius). For steel the temperature raise along a straight scan line just before the next pulse will strike on the surface is shown in Fig. 6. The position 0 denotes the position where the last pulse striked the surface. Due to the accumulation of the temperatures from previous pulses, the maximum value is located behind this position. The corresponding repetition rates and marking speeds are also denoted in Fig. 6. It is obvious that the value of the critical temperature raise will be exceeded for an average power between 50 and 60 W, i.e., the scale-up process will not be possible for steel with this spot size and pitch.

A similar simulation was performed for copper. Here, the repetition rate raises from 1.9 MHz at 40 W average power to 5.74 MHz at 120 W. The corresponding marking speeds would range from 21 up to 65 m/s, and the maximum temperature raise will range from 200 up to 500 °C.

For copper and other metals having a threshold fluence in the same order, no problems are expected to inhibit the scale-up process. However, for steels, principally showing

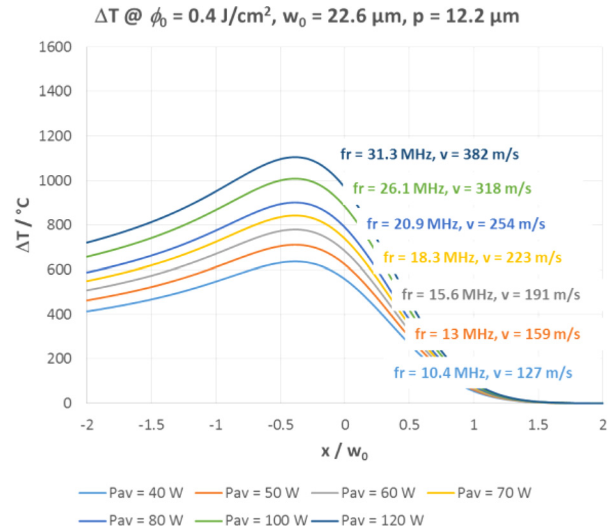

FIG. 6. Temperature raise, just before the next pulse strikes onto surface, along a straight scan line for different average powers. $x = 0$ denotes the position of the previous pulse.

small threshold fluences and cavity formation, alternative strategies have to be developed.

C. Adapted strategies

1. Enlarging the pitch

Even the maximum speed of the used LSE-170 polygon scanner amounts 100 m/s, it is possible in principal to achieve higher speeds.[15,16] Therefore, simulations for an average power of 100 W and different pitches were done, and its results are shown in Fig. 7. To maintain a maximum temperature raise around 700 °C, the pitch should be set to 24 μm corresponding to a marking speed of 625 m/s. Beside this high marking speed also the high pitch could cause

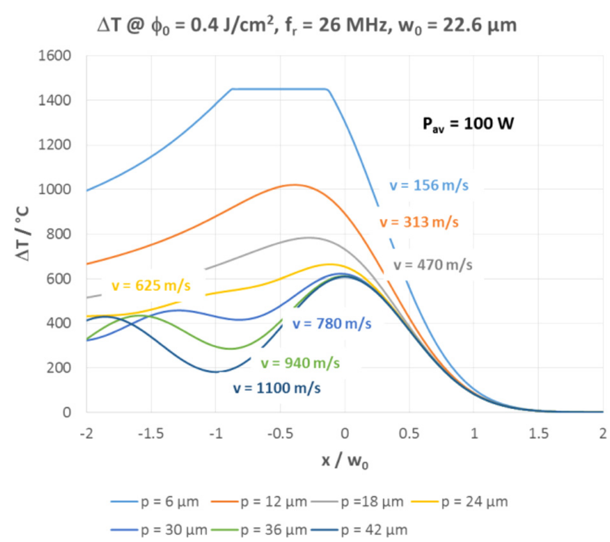

FIG. 7. Temperature raise, just before the next pulse strikes on the surface, along a straight scan line for an average power of 100 W and different pitches. $x = 0$ denotes the position of the previous pulse. The flat part of the light blue line denotes the region the phase transition to the melting phase is located.

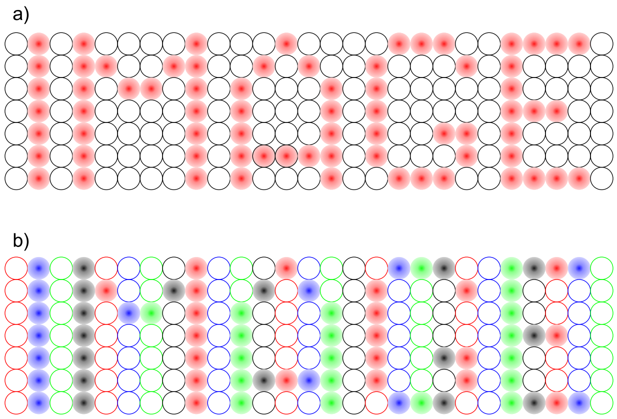

FIG. 8. Illustration of the "interlaced mode": the spot pattern (a) is realized with a sequence of four patterns having four times higher pitch. Case of clarity a spot to spot distance of one diameter was chosen.

problems as a higher surface roughness will be achieved with pitches exceeding a spot radius.[7]

Principally, the distance between two spots on the surface can be reduced by an interlaced mode. A spot pattern as shown in Fig. 8(a) can be divided in n sub-patterns with n times the distance between two spots, indicated with different colors in Fig. 8(b). These sub-patterns are then marked one by one and finally the situation of Fig. 8(a) is obtained.

The influence onto the surface roughness was investigated by machining squares with the synchronized Galvo scanner setup with $n = 1$, 2, 3, 4, and 6. The results for the measured depths and surface roughness s_a (deduced following ISO 25178) are shown in Fig. 9. No significant differences are observed neither for the depth nor for the roughness. Therefore, this strategy was also tested with the polygon line scanner as shown in Fig. 10. A pitch of 4.9 μm marked with 40 m/s was compared with a sequence of two patterns having a pitch of 9.8 μm marked with 80 m/s. Additionally, a pitch of 3.05 μm at 25 m/s is compared with a sequence of four patterns with a pitch of 12.2 μm at 100 m/s. All experiments were performed with the maximum average power of the laser system of 42.8 W.

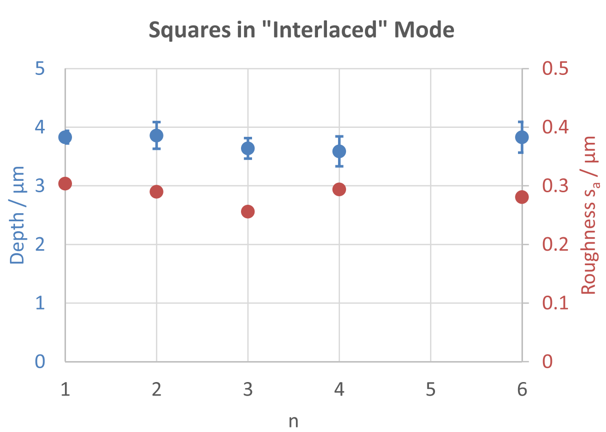

FIG. 9. Illustration of the "interlaced mode": The original spot pattern a), where filled circles mean laser on and empty circles laser off, is realized with a sequence of 4 sub-patterns b) having 4 times higher pitch (red, blue, green, black). These sub-patterns are machined one by one to obtain the original pattern a). Case of clarity a spot to spot distance of one diameter was chosen in this illustration.

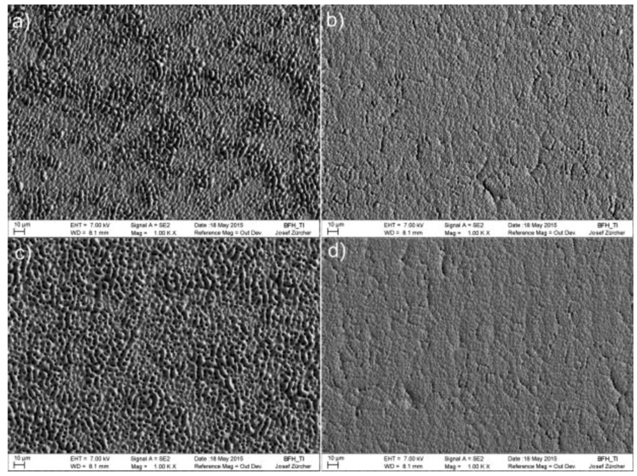

FIG. 10. Test of interlaced mode with the polygon line scanner: (a) surface machined with a pitch of 4.9 μm. (b) Surface machined with a sequence of two patterns with a pitch of 9.8 μm. (c) Surface machined with a pitch of 3.05 μm. (d) Surface machined with a sequence of four patterns with a pitch of 12.2 μm.

The surfaces machined with the small pitch, Figs. 10(a) and 10(c) show cavity formation whereas the surfaces machined with the sequences but finally having the same distance between two spots show a good surface quality. Therefore, one can conclude that the interlaced mode will work but will demand very high marking speeds of several 100 m/s and repetition rates of several 10 MHz where single pulse switching will definitively not be possible any more.

2. Enlarge the spot size

A second strategy deals with bigger spot sizes, e.g., by enlarging the spot radius by a factor of k its area is scaled by k^2, i.e., the pulse energy has also to be k^2 times higher if the fluence is kept at the same value, and therefore, assuming the same average power, the repetition rate has to be divided by this factor k^2. Following Eq. (2), the marking speed would be divided by k if the overlap is kept. Finally, one marks with a k times slower speed and a k^2 smaller repetition rate and therefore a reduction of the heat accumulation is expected. This expectation is also confirmed by the simulation which predicts that with a spot radius of about 40 μm, the temperature raise would be around the critical value for 100 W of average power. The corresponding repetition rate and marking speed would be 8.3 MHz and 165 m/s, respectively. This marking speed is still not accessible with the existing polygon line scanner. Therefore, a second simulation was performed with a constant marking speed of 100 m/s by adapting the overlap. The corresponding results are summarized in Fig. 11. With a spot size of 45 μm, the critical temperature is reached and the corresponding repetition rate amounts 6.6 MHz which will definitively accessible with the new laser system. But enlarging the spot size will of course reduce the precision and enlarge minimum achievable structure size. Further the reduction of the spot size will be achieved by a smaller diameter of the laser beam at the scanner input. It has to be clarified first if the mirror coatings of the f-theta optics inside the scanner are able to deal with the corresponding high intensities.

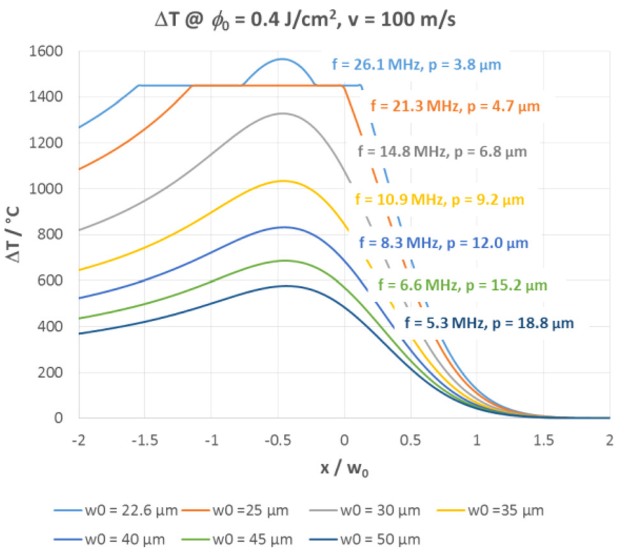

FIG. 11. Temperature raise along a straight scan line, just before the next pulse strikes onto surface, for an average power of 100 W and a marking speed of 100 m/s for different spot sizes. $x = 0$ denotes the position of the previous pulse. The flat part of the light blue and orange lines denotes the phase transition to the melting phase. In the hump of the light blue line, all material is melted and the temperature can raise again.

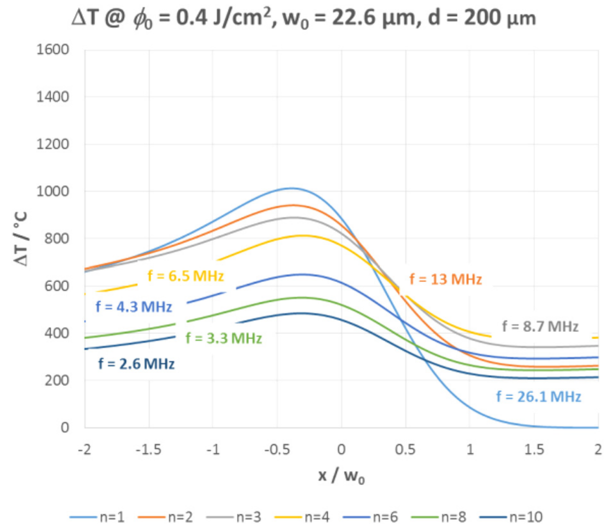

FIG. 12. Temperature raise along a straight scan line, just before the next pulse train strikes onto surface for different number of pulses spaced by 200 μm and for an average power of 100 W. $x = 0$ denotes the position of the first pulse of the previous pulse train.

3. Pulse bursts

Using an n-pulse burst and maintaining the energy of the single pulses in the burst would demand a n times smaller repetition rate and also marking speed. Pulse bursts and the simulation of its temperature raise were discussed in detail in Ref. 20. It was found that the temperature raise of a n-pulse burst just before the next burst strikes on the surface does not significantly differ from a single pulse with n-times higher energy and same repetition rate. An additional simulation for 100 W average power, a spot radius of 22.6 μm, and a pitch of 11.2 μm showed that the surface temperature can be a little reduced by using a two-pulse burst. But with 1140 °C it rests far above the critical value. For a higher number of pulses per burst, the maximum temperature raises again and exceeds the value for a single pulse. Thus, pulse bursts are not suited to machine steel with 100 W of average power.

4. Multi spot processing

Another possibility is to use multiple of spots. Dividing the beam into n spots would reduce the corresponding repetition rate by a factor of n. Multispots can either be obtained by a diffractive optical element[21] or with a spatial light modulator[22] giving more flexibility. Of course, the temperature distribution will depend on the exact spot pattern. As an example, the temperature raise of a sequence of *n spots arranged along the scan line with distance d* was calculated. For an average power of 100 W, a spot radius of 22.6 μm and a spot distance of 100 μm at least ten spots would be needed if the critical temperature should not be exceeded. With increasing spot distance, the temperature raise on the surface decreases and the results for a spot distance of 200 μm are shown in Fig. 12. In this case, six or more spots would lead to a maximum temperature raise below the critical value.

V. CONCLUSION

Surface texturing with ultrashort pulses and an average power up to 100 W was investigated by numerical simulations, which were backed up with experiments at lower average power. For metals like copper with high threshold fluences scale up into the 100 W regime with the existing polygon scanner setup should be possible without serious problems. But, for steels showing low threshold fluences, the power scaling is limited due to cavity formations. On the one hand, the pulse energy has to be kept at its optimum value, and on the other hand, heat accumulation has to be avoided. In case of steel 1.4301, the optimum fluence amounts about 0.4 J/cm^2 and the critical temperature raise on the surface just before the next pulse will strike onto it should not exceed a critical value between 600 °C and 800 °C. These conditions strongly limit the scale-up process, and adapted strategies have to be developed.

For small spots sizes, the marking speed has to be raised significantly up to several 100 m/s and the pitch will exceed one spot radius. To finally maintain a small distance between two spots on the target an interlaced mode can be used. However, the high marking speed and switching the beam on and off rest challenging.

The demands onto the repetition rate and marking speed can be reduced by enlarging the spot size. With the current setup and the new laser system, a spot radius of 45 μm should be suitable to work with 100 W of average power. But larger spots will reduce the precision and will also influence the minimum achievable structure size.

With multispots, the heat accumulation effects are significantly reduced but then additional elements as a diffractive optical element or a spatial light modulator are needed. It has to be clarified if such elements could be combined with the existing polygon line scanner. In addition, multispots would strongly reduce the flexibility of the setup but represent a good solution for special applications.

In summary, one can conclude that power-scaling for surface texturing of steel and other metals with low threshold fluences rests a big challenge and demands further efforts in beam guiding systems.

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