High-power nanosecond pulsed laser engraving with an ultra-high speed polygon mirror scanner

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Increasing speed in laser processing is driven by the development of high-power lasers into ranges of more than 1 kW. Additionally, a proper distribution of these laser power is required to achieve high quality processing results. In the case of high pulse repletion rates, a proper distribution of the pulses can be obtained from ultra-fast beam deflection in the range of several 100 m/s. A two-dimensional polygon mirror scanner has been used to distribute a nanosecond pulsed laser with up to 1 kW average power at a wavelength of 1064 nm for multi pass laser engraving. The pulse duration of this laser can be varied between 30 ns and 240 ns and the pulse repetition rate is set between 1 and 4 MHz. The depth information is included in greyscale bitmaps, which were used to modulate the laser during the scanning accordingly to the lateral position and the depth. The process allows high processing rates and thus high throughput.

1. Introduction

Polygon mirror scanners has shown the capability to deflect lasers beams with ultra-high speeds up to 1.000 m/s and thus, to distribute high laser powers on the target material.[1] Hence, pulses in the MHz-range can be separated from each other to avoid overlapping and heat accumulation. However, multi-pass treatments allow high ablation depths and also drilling.[1-6] Polygon mirror scanners have been used to ablate material into depth using continuous wave laser, nanosecond pulsed and ultra-short pulsed lasers. With the polygon mirror scanner 500 W average power have been used in the nanosecond pulsed regime.[2] The following study shows the utilization of up to 1 kW laser power obtained in a 30 - 240 ns pulse duration regime with up to 4 MHz pulse repetition rate.

2. Experimental

A polygon mirror scanner of the PM-series (MOEWE Optical Solutions) was used together with two different nanosecond pulsed fiber lasers (IPG Photonics). Both lasers are working in a range from 30 – 240 ns with a maximum average laser power of 500 W and 1 kW. The maximum available laser pulse repetition rate varies between 1 and 4 MHz depending on the pulse duration. The 1 kW laser is additionally capable to adapt the pulse frequency to an external clock signal. The wavelength is 1064 nm in both cases.

The polygon mirror scanner was equipped with a f-theta optics with focal length of 255 mm. The scan speed was varied between 10 and 100 m/s. The scanner is able to send a position depended frequency signal, which can be used as clock signal for the laser to synchronize the laser frequency with the beam deflection.

The engraving experiments were performed with the 1 kW laser working with position synchronized pulses in the multi-pass ablation strategy, ablating only one per position and scan. To achieve a certain depth, the number of scan repetitions is adapted. The pulse-to-pulse distance is obtained from scan speed and pulse repetition rate. After the engraining, further investigations regarding material removal and surface quality have been

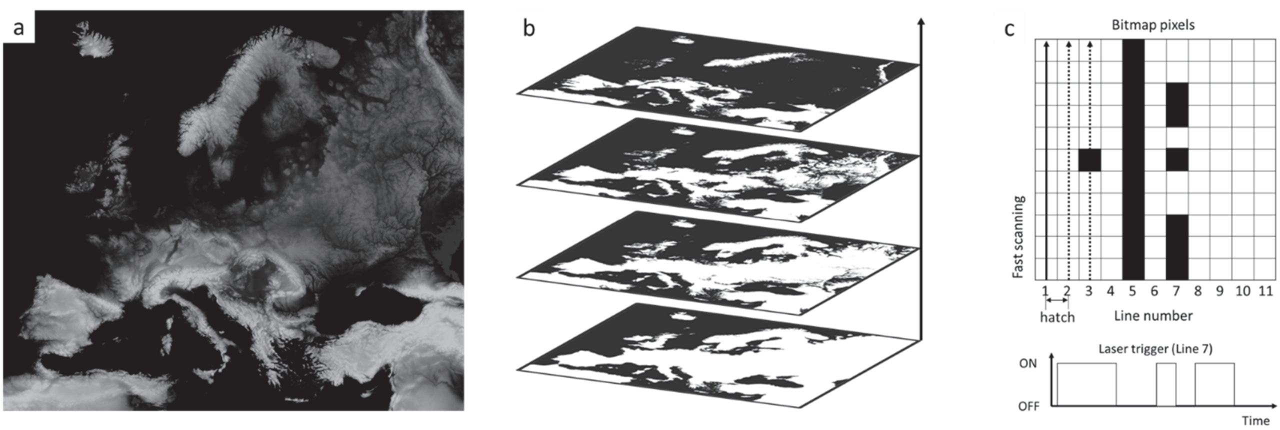

Figure 1: (a) 8-bit depth map of Europe with sea level in black (bit value 0) and mountains gray / white (up to 187), (b) illustration of black / white bitmaps per depth level as done in the FPGA logic of the polygon mirror scanner and (c) laser switching per scanned line according the bitmap value.

performed with the 500 W laser. All experiments were performed on stainless steel. The treated material was characterized in an optical microscope (KEYENCE) and the depth measurements were performed with a laser scanning confocal microscope (KEYENCE VK-X200 and OLYMPUS LEXT OLS 4100).

3. Results and discussion

The engraving process starts with the depth information, which is included in an 8-bit or 16-bit grayscale image (bitmap format), as shown in Figure 1 (a). The bitmap is loaded into the polygon scanner and scaled to the target size in x and y. The used depth map of Europe has a color depth of 8-bit from 0 (black) to 255 (white). The highest value is 187. The internal FPGA-based device and process controller can handle these 256-bit values as depth levels, layer-wise or coupled to a length scale (µm/bit) in all three dimensions of space. The process can run from 0 to 255 or inverse and are based on slicing the depth map into black/withe (0/1) bitmap for each height level (Figure 1 (b). After treating a layer, the logic goes to the next depth level defined by a bit counter or calculated from the current Z-position. For each level, the laser "ON" and "OFF" areas (displayed as black and white) are calculated from the grayscale image depending if the bit-value of a position is higher or lower as the current depth level position. Finally, for each depth layer and thus scan repetition another laser switching matrix (0/1 bitmap) is used. Figure 1 (c) illustrates, how the scanning process is steered by the polygon mirror scanner. For each scanned line, the correlating bitmap column is selected and the trigger signal for the laser is set high or low accordingly. The user can easily switch between "on" related to white or black. Furthermore, it is user selectable either areas below the current depth level are treated or areas above. Using the smaller "<" comparator, all areas below the current depth (Z position) are treated. In the case of the chosen Europe map, the sea level (black) is treated in every repetition, while the highest point is treated only once. As result, a relief with mountains higher than the water is created as shown in Figure 2 (a).

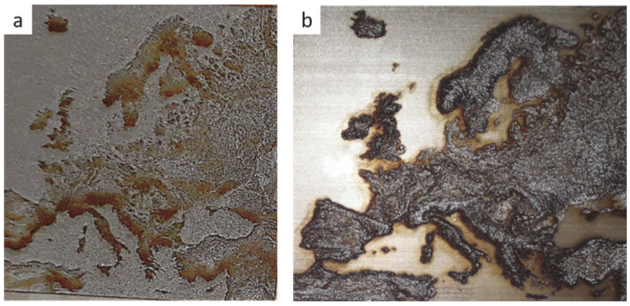

Figure 2(a) True relief strategy of the engraved Europe with 187 scans at 30 ns with 100 m/s takes 28 minutes, (b) inverse strategy with mountains engraved into stainless steel with 187 scans at 60 ns pulses at 50 m/s takes 55 minutes. In both cases the 0,25 mJ pusle energy and 4 Mhz repetition rate are used to treate a 40 x 40 mm² are.

Choosing the larger ">" comparator, all areas above the current level are treated, resulting in an inverse relief with mountains deep engraved into the material, while the water is not treated as shown in (Figure 2 (b).

In the first case, the sea level is the lowest one with the largest number of scan repetitions. Since the highest value of the bitmap is 187, also the process range is adapted to this value resulting in 187 scans in the sea level areas. The laser was set to 30 ns pulse duration with 0,25 mJ pulse energy and a repetition rate of 4 MHz. The scan speed was 100 m/s resulting in a pulse-to-pulse distance of 25 µm, the line spacing is also 25 µm. The spot size, obtained from a LIU-plot, is 53.6 ± 3.9 µm. Consequently, the average fluence is 11.1 J/cm². The depth can be measured very easily at the edge of the treated area, as visible in Figure 3 (a). The maximum depth is measured to be 251 µm obtained from 187 scans. Thus, the average depth per scan repetition is 1,34 µm. Within the ablated region, a high roughness can be observed resulting a strong depth variation. Of

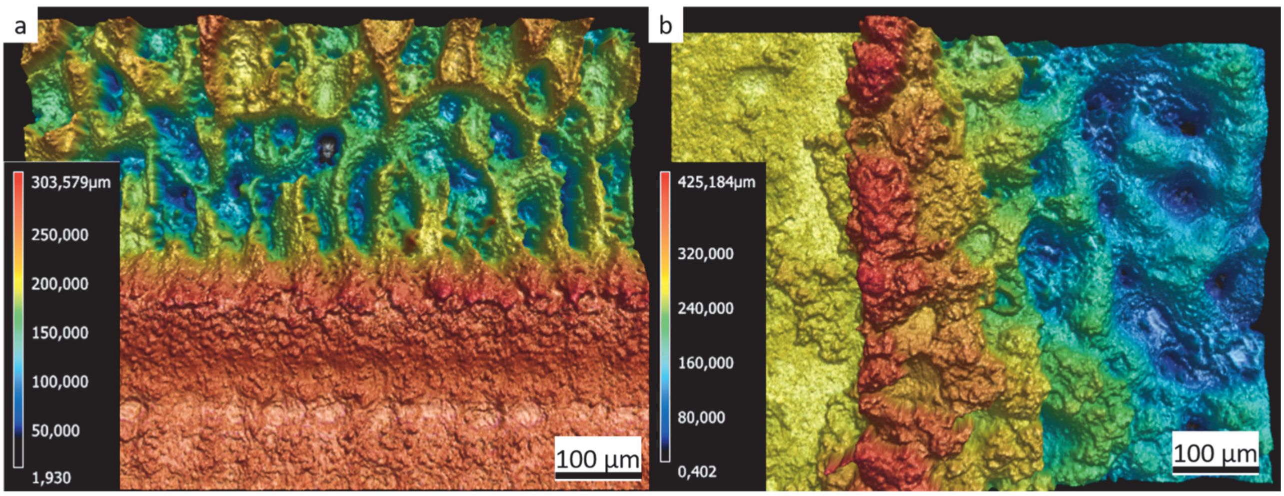

Figure 3: (a) Confocal image of the true relief strategy with the inial surface (red) and the deep engraved sea level in the upper part. A high surface rougthness up to Rz = 166 µm can be observed in the multi pass treated areas, (b) the inverse strategy with mountains engraved into the deep (blue) and the visible ridge formation (red) at the edge of the machined area. Th initial surface level is visible on the left side (yellow)

160 µm. At the edge of the machined area, a ridge of ablation products can be observed, which is smaller than 30 µm in height. The roughness was determined using profiles to be Ra = 26 µm, Rz= 166 µm and using surface measurements to be Sa =35 µm Sz=294 µm. This Rz and Sz values fits well to the different in depth measured from the profiles. In the center of the relief a comparison between high mountains and the see level is not possible since the roughness is higher, than the average depth difference.

In the invers process, the depth was measured from the non-treated sea areas into the deep engraved mountain areas as shown in Figure 3(b). Here a depth of 390 µm can be measured, obtained from 187 repetitions. This equals an average depth per scan of 2,1 µm. The pulse duration was set to 60 ns. The power of 1 kW was obtained from 4 MHz repetition rate with 0,25 mJ pulse energy. The scan speed was 50 m/s with a pulse-to-pulse distance of 12,5 µm, while the line spacing is 25 µm. The spot diameter is measured to 48.7 ± 1.7 µm resulting in a fluence of 13.4 J/cm². Thus, the deposited energy per line is twice compared to the first case, but the number of repetitions is reduced. At the edge, where a deep engraved area (183 µm) is directly borders to the non-machined area, A ridge formation of up to 165 µm height can be observed. Compared to the first process, the engraved areas are deeper. Here the engraved cavities are limited in the lateral size and the ablation products can be deposited in the neighbored less treated areas under massive ridge formation. While in the first case, the main part of the surface was treated with the maximum number of repetitions and the ablation products are deposited in the working zone and are treated again and again in every scan repetition. Thus, the majority of the melted material during the laser treatment resolidifies in the neighbored scan paths and is just moved within the machined area, but it is not ejected from the substrate. Thus, the nanosecond pulsed ablation with the 1 kW average laser power and scan speed up to 100 m/s is able to treat a lot of material in a short time, but the insufficient material ejection in the used parameter settings results in ridge formation and rough surfaces.

A comparison of the processing time shows, that the second process takes twice the time of the first one, 55 and 28 minutes, respectively. The reason is the reduced scan speed of 50 m/s compared to 100 m/s in the first case. Although the area of engravement is much smaller compared to the first process, all lines in all layers are passed, even if only a small part is treated and also if no part is treated. In fact, an optimization can be done by skipping empty lines, which will be respected in the furture development of the processing logic. Lines with a small amount of processing length cannot be skipped. However, the used length of 40 mm in the fast-scanning direction can be prolonged to 100 mm without additional time. Thus, the treated area can be increased by factor 2.5, due to a better utilization of the polygon facet. On contrary, an enlargement in slow axis would increase the processing time proportional.

4. Conclusion

A two-dimensional polygon mirror scanner has been used together with a 1 kW nanosecond-pulsed NIR-laser to engrave a grayscale depth map into a stainless-steel substrate. Thereby the real-time logic of the scanner controlling the laser process and is able to handle a depth map in order to engrave this data level by level. Macroscopic, the depth is transferred clearly visible. Microscopic, high ablation can be obtained from the high-power laser, but the quality of the resulting rough surface can be improved. The high amount of ablation debris and resolidified melt within the machined avoid a smooth surface and thus a defined processing into the depth. Further investigations have been started to improve the surface quality in order to more accurate depth levels.

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