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Factors influencing laser material removal process in micro cavity manufacturing

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Abstract Laser processing of engineering materials is a well-established process. Latest developments in laser sources offer enormous flexibility but also present challenges. Laser material interaction regulates the material removal process and correct laser parameters are key to a successful processing. Complex micro cavities can be produced by material removal in a layer by layer fashion. Large number of laser and material characteristics influence the process but a single crater formation governs the process as material is removed by overlapping single craters.

1. Laser material removal process

The laser milling process removes material as a result of interaction between the laser beam and the substrate or work piece [1, 2]. Several removal mechanisms can take place, depending on a number of process parameters related to the beam and the work piece material. The following subsections describe some of the factors influencing the laser milling process. A number of techniques for laser milling has been developed. These techniques differ from one another in the applied laser source, the relative beam/work piece movements and the laser spot characteristics. A common feature of all laser milling techniques is that the final part geometry is created in a layer-by-layer fashion by generating overlapping craters [3]. Within a single layer, these simple volumes are arranged in such a manner that each slice has a uniform thickness. Through relative movements of the laser beam and the work piece the micro craters produced by individual laser pulses sequentially cover complete layers of the part.

2. Laser and machining parameters and their influence

Laser milling means that the material removal is accomplished by the laser-material interaction in succession. Laser material interaction is localized, non–contact machining and is almost reaction–force free. Photon energy is absorbed by the target material in the form of thermal or photochemical energy. In case of pico- and femtosecond laser pulses, material is removed by direct vaporization/sublimation.

In general, optimal laser micromachining is achieved when photons are strongly absorbed by the substrate. Furthermore, if these photons are delivered in a short duration pulse, a mini explosion is created ejecting solid and gaseous particulates from the irradiated target without significant thermal damage (melting, spatter, recrystallization, etc.) occurring in the surrounding area.

The system removes material in layers with a predefined thickness. As mentioned previously, each single layer is machined by overlapping a sequence of micro cavities. The two-dimensional data obtained by slicing the volume to be removed are used to programme the system.

Two hatching parameters, the track displacement and the distance between the end of the hatch line and the last border cut, are adjustable to tune the process. By increasing the scanning speed and making the track displacement larger than the laser spot diameter, the single pulse craters along the path of the laser beam can be separated from one another by varying the scanning speed and track displacement. Figure 9 illustrates the layer by layer fashion of material removal.
Due to the natural variances of the material properties, laser beam stability and output performance material removal may not be uniform throughout the entire process. Below explanation is given for some of the parameters that directly affect the laser removal process.

Laser pulse energy

The pulse energy Ep is simply the total optical energy content of a pulse. For single pulses, e.g. from a Q-switched laser, the pulse energy may be measured e.g. with a pyroelectric device. For regular pulse trains, the pulse energy is often calculated by dividing the average power (measured e.g. with a powermeter) by the pulse repetition rate. However, this is a valid procedure only if the energy emitted between the pulses is negligible. There are cases where, e.g., a mode-locked laser emits a pulse train together with a low-level background emission. Even if the background power level is far below the peak power, the background can significantly contribute to the average power. If, e.g., a photo detector has an insufficient dynamic range for testing this, it can be useful to test the conversion efficiency of a frequency doubler in a carefully controlled situation in the low-conversion regime.

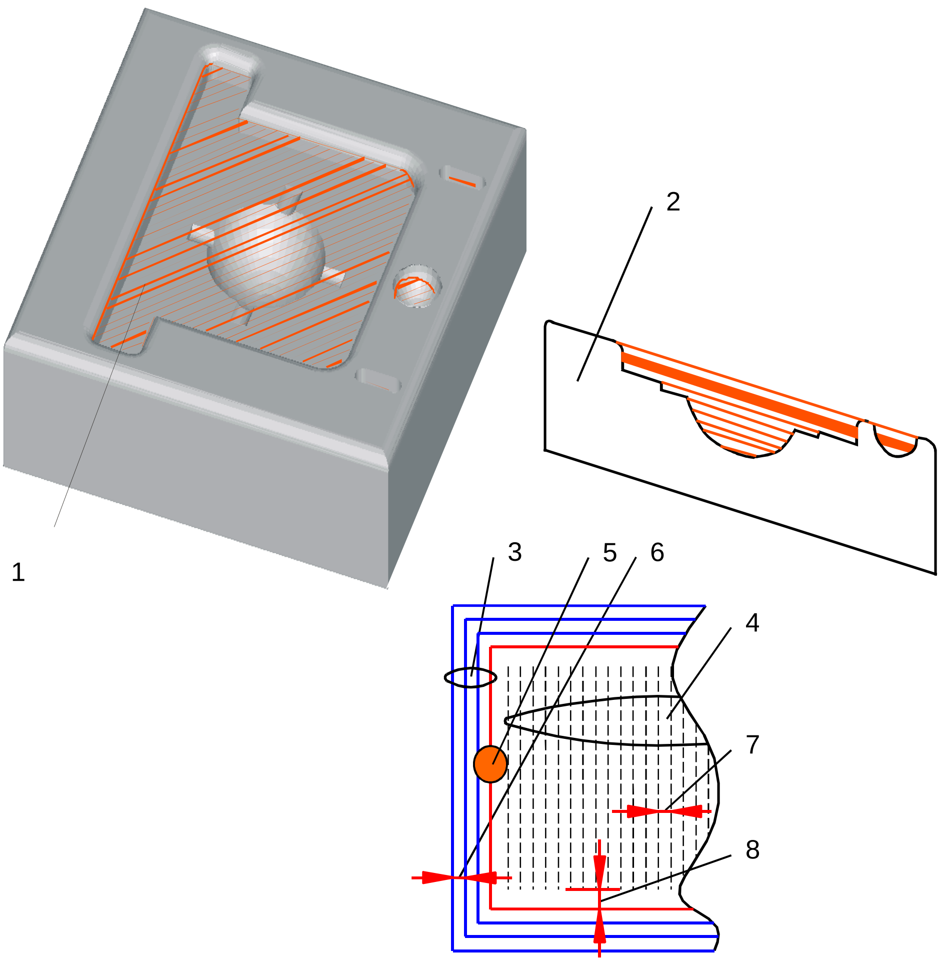

Figure 1 Material removal in the laser milling process [4]

1. cavity with a hatched slice
2. cross-section of the cavity with slices
3. border cuts
4. hatching cuts
5. laser spot
6. border cut track displacement (step-over)
7. hatch track displacement (step-over)
8. distance between the end of the hatch line and the innermost border cut

The pulse energy together with the pulse duration is often used to estimate the peak power of pulses. Conversely, temporal integration of the optical power results in the pulse energy.

Typical pulse energies from Q-switched lasers range from microjoules to millijoules, and for large systems to multiple joules or even kilojoules. Mode-locked lasers achieve much lower pulse energies (picojoules, nanojoules or at most a few microjoules) due to their high pulse repetition rates and sometimes due to limiting nonlinear effects in the laser resonator. Much higher energies of ultrashort pulses can be achieved by amplifying pulses at a lower repetition rate, as obtained e.g. with a pulse picker or a regenerative amplifier.

It is very easy to obtain the average laser power P, which enables the calculation of the laser pulse energy by:

$$E_p = \frac{P}{V}$$

Where V is the laser pulse repetition rate.

Peak power

The peak power of an optical pulse is the maximum occurring optical power. Due to the short pulse durations which are possible with optical pulses, peak powers can become very high even for moderately energetic pulses. For example, pulse energy of 1 mJ in a 10-fs pulse, as can be generated with a mode-locked laser and a regenerative amplifier of moderate size, already leads to a peak power of the order of 100 GW, which is approximately the combined power of a hundred large nuclear power stations. Focusing such a pulse to a spot with e.g. 4 μm radius leads to enormous peak intensities of the order of 4×10^{21} W/m^2 = 4×10^{17} W/cm^2. Peak powers in the terawatt range can be generated with devices of still moderate size (fitting into a 20 m^2 room). Large facilities based on multi-stage chirped-pulse amplifiers can even generate pulses with petawatt peak powers.

For handling the large numbers associated with high peak powers, the following prefixes are often used:

1 kW (kilowatt) = 10^3 W
1 MW (megawatt) = 10^6 W
1 GW (gigawatt) = 10^9 W
1 TW (terawatt) = 10^{12} W
1 PW (petawatt) = 10^{15} W

Measurement of Peak Power

For relatively long pulses, the peak power can be measured directly e.g. with a photodiode which monitors the optical power versus time. For pulse durations below a few tens of picoseconds, this method is no longer viable. The peak power is then often calculated from the (full width at half-maximum, FWHM) pulse duration and the pulse energy. The conversion depends on the temporal shape of the pulse. For example, for a Gaussian beam the peak power is:

$$P_p \approx \frac{0.94E_p}{\tau}$$

If pulses are subject to strong nonlinear pulse distortions or similar effects, a significant part of their pulse energy may be contained in their temporal wings, and the relation between peak power and pulse energy may be substantially modified.

Laser spot

The removal mechanism in laser milling is based on a single shot being repeated in succession. Therefore the size of the laser spot becomes a very important parameter. There are many factors affecting the laser spot – Laser source characteristics, optical components, etc.

Basically, the laser spot is given by the following equation [5]:

$$2w_o = \frac{4M^2\lambda f}{\pi D}$$

Where: λ is the wavelength of the laser source,
f is the focal length of the lens,
D is the input beam diameter,
M^2 is the beam quality factor

The M^2 factor, also called beam quality factor or beam propagation factor, is a common measure of the beam quality of a laser beam. According to ISO Standard 11146 [6], it is defined as the beam parameter product divided by λ / π, the latter being the beam parameter product for a diffraction-limited Gaussian beam with the same wavelength. In other words, the beam divergence is

$$\theta = \frac{M^2\lambda}{\pi w_o}$$

where w_0 is the beam radius at the beam waist and λ the wavelength. A laser beam is often said to be "M^2 times diffraction-limited". A diffraction-limited beam has an M^2 factor of 1, and is a Gaussian beam. Smaller values of M^2 are physically not possible. A Hermite–Gaussian beam, related to a TEM_{nm} resonator mode, has an M^2 factor of (2n + 1) in the x direction, and (2m + 1) in the y direction.

The M^2 factor of a laser beam limits the degree to which the beam can be focused for a given beam divergence angle, which is often limited by the numerical aperture of the focusing lens. Together with the optical power, the beam quality factor determines the brightness (more precisely, the radiance) of a laser beam.

For non circularly symmetric beams, the M^2 factor can be different for two directions orthogonal to the beam axis and to each other. This is particularly the case for the output of diode bars, where the M^2 factor is fairly low for the fast axis and much higher for the slow axis.

According to ISO Standard 11146 [6], the M^2 factor can be calculated from the measured evolution of the beam radius along the propagation direction (i.e. from the so-called caustic). A number of rules have to be observed, e.g. concerning the exact definition of the beam radius and details of the fitting procedure. Alternative methods are based on wavefront sensors, e.g. Shack–Hartmann sensors, which require the characterization of the beam only in a single plane [7].

Note that the M^2 factor, being a single number, cannot be considered as a complete characterization of beam quality. The actual quality of a beam for a certain application can depend on details which are not captured with such a single number.

The concept of the M^2 factor not only allows one to quantify the beam quality with a single number, but also to predict the evolution of the beam radius with a technically very simple extension of the Gaussian beam analysis: one simply has to replace the wavelength with M^2 times the wavelength in all equations. This is very convenient for, e.g., designing the pump optics of diode-pumped lasers. Note, however, that this method works only when a certain definition of beam radius is used which is also suitable for non-Gaussian beam shapes; see again ISO Standard 11146 [6] for details.

Working in focus

During the material removal process ensuring stable and uniform removal process is of vital importance. System will change the Z levels during processing accordingly to the program, but if actual removal does not correspond to the programmed values soon the process performance will deteriorate and there is a high probability removal will stop completely. Figure 2 illustrates changes in spot diameter as a result of changing the focal position.

The line width near the scale bar where the laser beam is in focus measures around 20 micrometres, where at the last line below the line width increases to around 45 micrometres. There is significant change in the depth achieved as well.

Difference between two neighbouring lines is only 50 micrometres in Z (vertical axis).

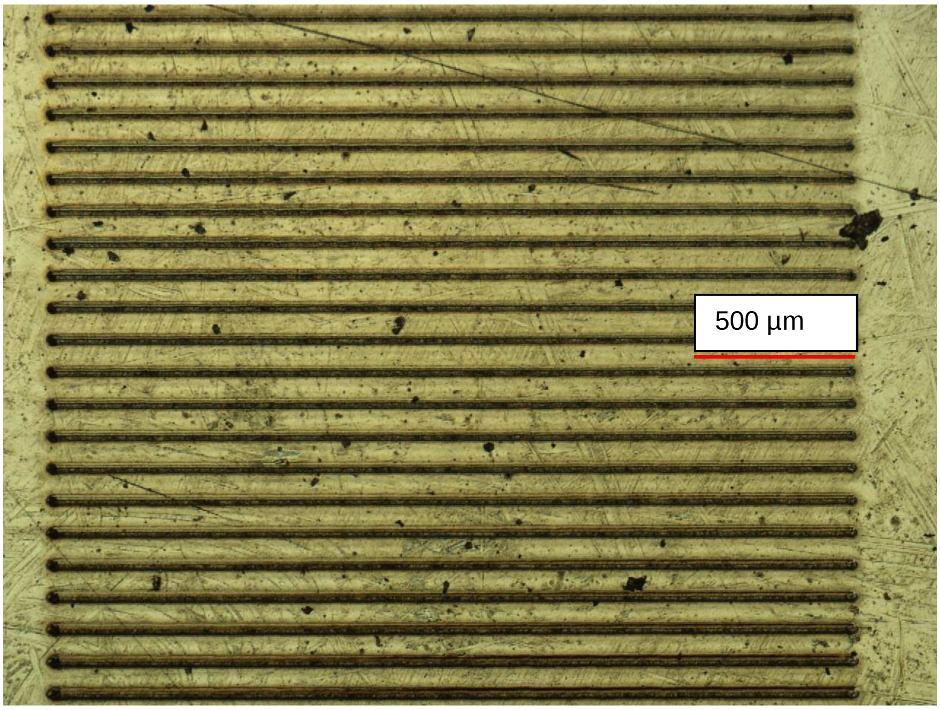

Figure 2 Focus scan lines

3. Roughness and depth achieved as a result of overlapping of single craters

3.1 Set up and parameters

In order to investigate the influence of the crater overlap on removal depth and surface quality – an experiment was conducted. Typical laser parameters were selected and details are given here below:

- Power 70% (9.55 W)
- Pulse length 10µs
- Repetition rate 30 kHz
- Scanning speed 300 mm/s

The material selected for this experiment was stainless steel BS316.

In order to eliminate the influence of the scanning direction – 5 layers were ablated, rotating the angle in a random fashion to ensure uniform material removal.

The following cleaning procedure was followed:

- Gentle ultrasonic cleaning
- Chemical cleaning (Savan 200).
- Gentle ultrasonic cleaning.

All these steps were taken in order to clean the specimens, whilst preserving the topology for further measurements.

All measurements were taken using a white light profiling microscope. The size of the scanned areas was chosen according to ISO 4288:1996 and ISO 11562:1996 [8]. The parameter used to evaluate the surface roughness was the arithmetic mean roughness (Ra) because relative heights in micro topographies are more representative, especially when measuring flat surfaces.

3.2 Results

The results are shown in Figure 3. Data includes results from roughness measurements in each filed, actual depth achieved and calculated percentage of overlapping.

Overlapping distance	Roughness achieved Ra	Depth achieved	Overlapping
µm	µm	µm	%
0.5	3.5	52	97.5
1	3.1	51.26	97.2
5	3.29	20.88	85.9
10	1.62	12.16	71.9
15	1.94	7.42	58.4
20	1.7	5.21	45.3
25	1.84	4.98	33.1
30	1.8	3.14	21.9
35	2.42	3.57	12.1
40	2.6	2.59	4.4

Figure 3 Roughness and depth achieved by varying the overlapping

Figure 4 shows depth as a result of the overlapping distance.

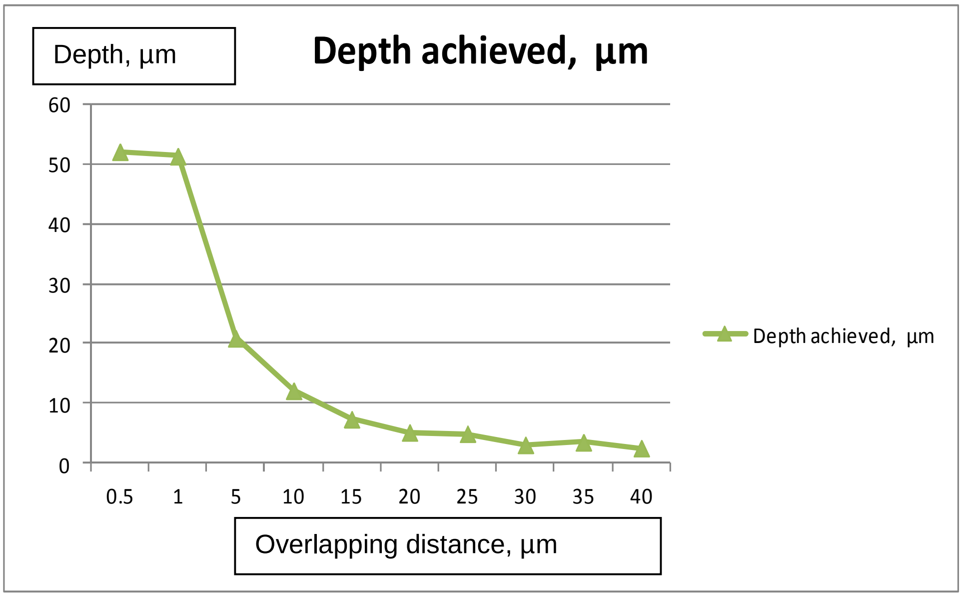

Figure 4 Depth achieved

Typical laser spot diameter for this experiment was around 45µm so when the overlap is much smaller it causes a large material removal but also very poor quality of the ablated surface. Initial depth achieved quickly plummets as the space between craters increases until it reaches around space between craters of 20 µm. Then the character of the curve changes to less dramatic change in the resulting depth. After 40 µm space between craters the process changes as there is virtually no overlapping hence the region beyond 40 µm overlap is of no interest for this study. It should be noted that any change in the power output and/or repetition frequency will result in change of the effective laser spot due to the change in the pulse energy. So all these results presented in Figures 4, 6 and 7 will shift accordingly.

The new generation of fiber laser sources present a new challenge as they exhibit non Gaussian temporal distribution of the beam shown in Figure 5. There is a significant difference in the temporal distribution of the pulses generated by this laser source. Shorter pulses are more like Gaussian but longer pulses have a specific shape. The intensity forms a peak at the beginning then there is a holding region where it does not change a lot followed by a rapid decline. This directly influences the laser material interaction as the initial contact might change the material state hence changing the absorption and effective crater formation.

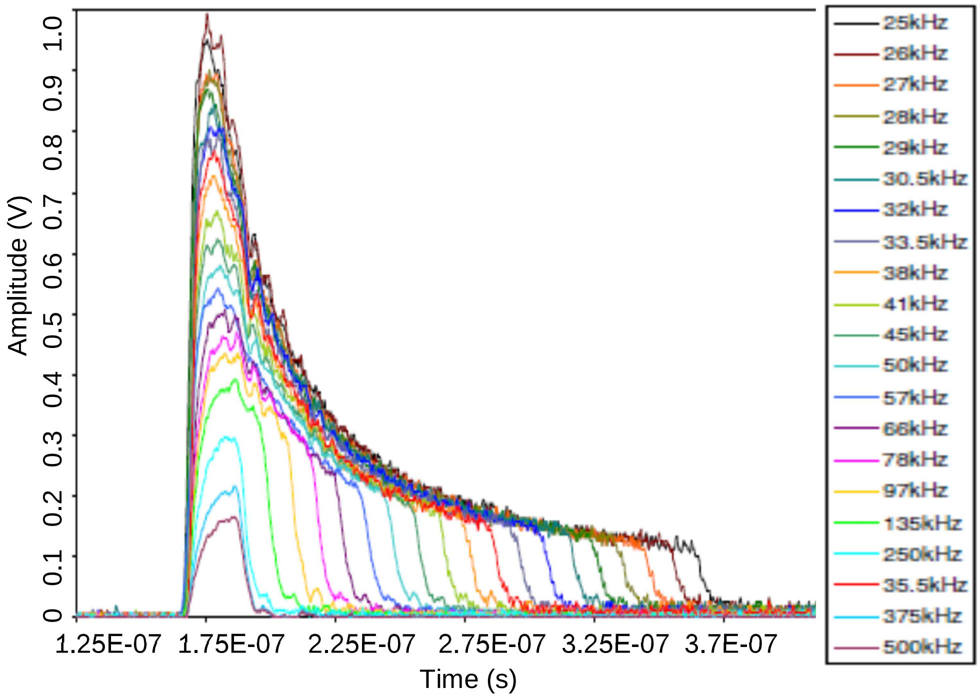

Figure 5 Family of fiber laser pulses

Figure 5 shows roughness as a result of the overlapping distance

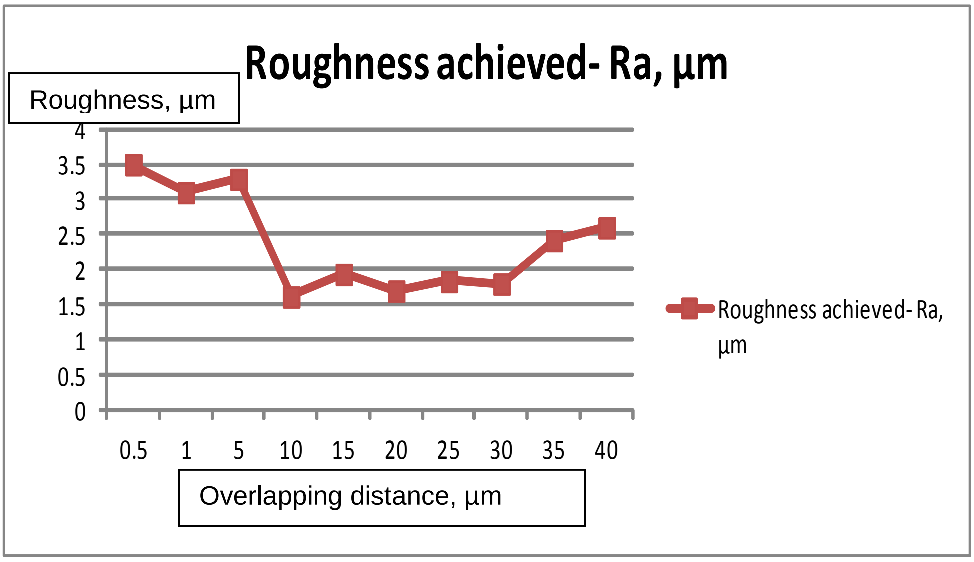

Figure 5 Roughness achieved

Roughness achieved presents strange phenomena. In a few places the roughness achieved is very close or virtually identical but that is achieved with completely different parameters. The main difference comes from the processing time as overlapping (Figure 6) is achieved by varying the scanning speed.

Figure 6 shows the overlapping of the spot area in percentage.

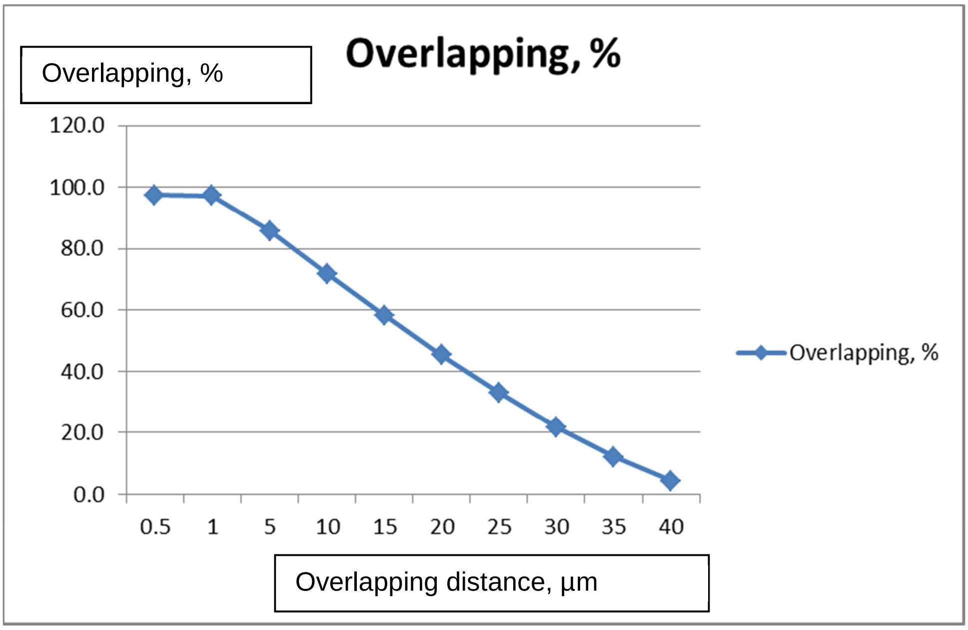

Figure 6 Overlapping percentage

3.3 Discussion

The best results in terms of roughness were achieved with 10 micrometers overlapping, or ~72 % overlapping, of the craters. When establishing laser parameters this should be taken into account as sometimes results are close, but depending on the optimisation criteria different sets of parameters could be preferred.

4. Conclusions

Laser milling is capable of processing a large range of materials which are not machinable with conventional manufacturing processes.

Nevertheless, laser milling is still in its infancy. Laser-material interactions are not yet fully understood. Much effort in the research and development of the available laser sources is still required. Ultrafast lasers are beginning to be applied. They can offer more precise machining without the thermal damage that accompanies long-pulse laser manufacturing.

The aim of this work was to investigate the effects on the substrate caused by laser ablation when utilized in 'milling' fashion and especially the roughness and penetration depth.

Acknowledgements

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