Development of high power femtosecond laser microstructures on automotive stainless steel

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Abstract. It is indispensable for the industry to introduce the most accurate manufacturing technologies. Therefore, laser beam machining centres have been gaining popularity in machining equipment over the last few years. We can perform quick and highly accurate machining with the latest generation of laser equipment which operates in femtosecond pulse mode. The purpose of this study is to find the best femtosecond laser surface machining technique on stainless steels by changing technological parameters. We have compiled a general table that lists the parameters, with variable values in bands and columns to select the most accurate surface treatment with minimal heat affected zone.

1. Introduction
Industrial participants consider it essential the precise and accurate adjustment of the processing, treatment technologies. It is not enough to buy a production equipment from a distributor, the company’s engineers are expected to program it according to their expertise for any process. This enables fast and complete product production on the machine.

Laser beam machining centers have been growing in popularity for decades, but over the past few years, they have seen a surge in popularity. Most of the equipments used by the industry are high performance continuous wave lasers. However, laser source manufacturers now have being able to build ultra-short-pulse laser equipment with above average performance. In short pulse laser beam machining, at about 300 fs, the laser peak power can reach a nuclear power plant’s power [1], this results in a whole new kind of laser beam-material interaction [2]. Thus, it is extremely important to know and explore the processes that occur when using these devices.

The absorption of high-power electromagnetic waves in metals causes hyper-sublimation, because of this, the metal changes from a solid state to a direct plasma state [3]. This phenomenon has minimal thermal effects and makes micromachining possible. With such applications, vascular stents, microfluidic channels, surface microstructures, channels can be formed in metals, depending on the appropriate parameters [4, 5]. Furthermore, with this technology we can make different surface engineering on materials without damaging the base material [6, 7].

Our aim was to investigate the effect of the different laser impulses on stainless steel using various laser frequency and impulse burst number. According to the different parameters the paper should reveal the difference between the material removals methods. The key goal was to find the best sharpening edges' grooves, micro structured by the femtosecond laser impulses. This application can be used as a
preparation of different joining technologies, micro structuring working surface of polymer and metal injection molding tool and change the wettability behaviors on the surface.

2. Materials and Methods
In our study we used stainless steel (AISI 304), one of the most common type of corrosion resistant steels. Before the laser machining, the surface of the steel was cleaned with methanol.

The laser treating process was performed using a Coherent Monaco Femtosecond Laser with wavelength of 1035 nm. The laser impulses had 277 fs of width and the average power was set between 2 W and 40 W (i.e. from 5% to 100% power). The beam was focused on the surface with a diameter of 80 µm.

Due to the pulses of the laser, the lines were constructed from points. First, it was necessary to determine the optimum distance between the points, where the resulting pattern resembles a single line. The laser beam diameter was 80 µm, therefore, we had to choose shorter distances. We set the distances, 60 µm, 50 µm, 40 µm, 30 µm, 20 µm, 10 µm, 5 µm. After that we examined with microscope which distance was the ideal to create a solid line, as shown in Figure 1.

![Figure 1. Distances between the laser spots A)50 µm, B)40 µm, C)30 µm, D)20 µm, E)10 µm, F)5 µm](image)

After examining the results, we found that the optimal distance is 10 µm.

After that we created a parameter table showing the power values and the number of pulses fired at one point. We draw four lines with each parameter, but repeated different times. First line wasn’t repeated, second was repeated 10 times, third was repeated 100 times, fourth was repeated 1000 times. The test was performed on both 188 kHz and 50 MHz. The final table is shown in Figure 2.
Figure 2. Parameter table: in all rectangles the first line wasn’t repeated, second was repeated 10 times, third was repeated 100 times, fourth was repeated 1000 times.

After completing the table with the different parameters, we used microscope to examine the different lines to determine which parameters makes the optimal results.

3. Results
If we look at the best results between Figure 4 and Figure 5, we get different results.

At 50 MHz, good lines are created at higher power, and pulse numbers can be counted between 1000 and 10000 and in general 100 repetitions proved to be appropriate. While at 188 kHz, line quality was the best around 25% average power. In terms of pulse numbers, it was clear that there were mainly 1, up to 10 pulse numbers that characterized good images. With this parameter 100 repetitions proved to be the optimal setting.

Examining the two tables, it is striking to see what frequency was characteristic. At 50 MHz, with little pulse and power, almost no material removal occurs. We only got the first test value after 100 pulses. This is due to the fact that at such high frequencies the laser is able to emit less power. At 188 kHz, it has a lower frequency, allowing it to emit more pulses per cycle, and the laser operates at a much higher average power. This is also evident in the heat input, it removes much more material at a lower frequency and thus the heat affected zone is larger.

In our research, we examined all the results for the thickness of the machined lines and the heat affected zone. Figure 3 illustrates which parameters and widths we specifically examined.
These values have been tabulated for both frequencies. First, we examined the machining width. The values of the two frequencies are plotted in a separate diagram.

At 50 MHz, it is clear that the width of the machined structure is also likely to increase with pulses which shown in Figure 4. This is around 80 µm, but if the pulse rate is higher than 10,000, this width will increase by leaps and bounds with higher power.

![Figure 3. Examined widths](image)

**Figure 4.** 50 MHz machining width as a function of pulses

Similar results can be observed at 188 kHz as shown in Figure 5. At low power, the width increases proportionally, but at 50% power, 1000 pulses are enough to make the 80 µm spot diameter works 3x wider.
After analyzing the working widths, we examined the heat affected zone. In the same way, we used to evaluate widths in diagrams. In most cases it was measurable, but at higher impulses and power, the heat effect was sometimes so large that we could only estimate the width.

Also starting a 50 MHz, it can be seen that above 50% the amount of heat input increases drastically at 100000 pulses, but below that it changes steadily between acceptable values as shown in Figure 6.

The same phenomenon can be observed at 188 kHz, but here we were able to examine several pulse ranges, so the diagram shows the changes better as shown in Figure 7. Also, over 50% average laser power, the heat affected zone increases after 100 pulses and can even reach width over 1 mm at higher power.
Figure 7. 188 kHz HAZ width as a function of pulses

The best structures were first selected by visual inspection. Compared to other similar patterns, we selected 2 images to show our results. Starting with the tests at 188 kHz, the results achieved there are shown in Figure 8. It is clear that the edges of the machining are sharp, forming a straight line. At this frequency, there was also enough lower power to get the structure right. The machining width is excellent, almost the same as the laser spot diameter, and the heat affected zone is.

Figure 8. Results reached at 188 kHz

The set parameters are as follows: Frequency is set to 188 kHz, power is set to 25%. The number of pulses is not significant, only 10, and the number of repetitions is also 10.

After that we also checked at 50 MHz, what settings were needed to achieve similar results. Figure 9 shows the successful test at 50 MHz.
Figure 9. Results reached at 50 MHz

The image has sharp borders, which also give a straight line along the machining. The heat effect is seen to be minimal here, as with the previous frequency. The exact parameters at 50 MHz are as follows: Machining at 100% power. Pulse count of 1000, which was recorded with 100 repetitions.

4. Conclusion
Laser beam technology is one of the best machining tools available today. Its industrial development is progressing in enormous pace, and developments are almost impossible to follow. It is gaining ground in every area, which is understandable as it allows them to do work that would be difficult to do by other means. More and more material removal and machining tools are being replaced by laser units, as developments give this vision. They are more economical, faster, more accurate, less energy intensive than their traditional counterparts. These devices are most suitable for developing microstructures. During our research we were able to create the appropriate surface structures.

Summarizing the results of our research:
- Laser parameters greatly influence the surface structure of stainless steel,
- 188 kHz and 50 MHz also have parameters that achieve the desired surface structure,
- 188 kHz, 25% average laser power, 10 pulses and 10 repetitions caused 84.2 µm width of the lines,
- 50 MHz, 100% average laser power, 1000 impulses and 100 repetitions caused 92.4 µm width of the lines,
- very precise machining can be achieved with both frequencies with minimal heat effect.

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