Optimization of material removal parameters by femtosecond laser pulses

Miklós Berczeli¹, Ferenc Tajti¹
¹Department of Materials Technology, GAMF Faculty of Engineering and Computer Science, John Von Neumann University, Hungary

E-mail: berczeli.miklos@gamf.uni-neumann.hu

Abstract. Lasers are widely used and have become indispensable in many areas. Their application is very advantageous in many cases, the technology is very fast and high-precision machining can be achieved. Lasers are increasingly used in the automotive, aerospace, electronics, and medical industries. With this technology, we can perform almost any kind of material processing whether drilling, cutting, welding or even heat treatment. The laser can be well integrated into various machining systems and well automated. With the advancement of technology, we are capable of producing femtosecond pulsed lasers which machines are capable of high peak performance. Because of the high peak power and short pulses, other physical phenomena occur when the laser interacts with the material, so the method of material removal is different from longer laser impulses. Their application is expected to provide a much more controlled, more precise material removal, with very good surface quality, free of burrs and other dirt and deposits. One of the most important benefits expected from the use of technology is the minimal or no heat affected zone. In our research we are looking for a parameter that can achieve the most accurate material removal with a smaller heat affected zone.

1. Introduction
Lasers have evolved a lot since their launch and many new types of lasers have been developed over the last 50 years. The increase in performance, continuous improvement in laser beam quality and the development of laser beam conduction offers new opportunities for expanding applications. Lasers are widely used and have become indispensable in many areas. Their use is very advantageous in many cases, the technology provides high precision and fast machining. Lasers are increasingly used in the automotive, aerospace, electronics and medical industries [1]. With this technology, we can perform almost any kind of material processing, stripping, drilling, cutting, welding heat treatment or even surface treatment [2-4]. Laser beam technology can be well automated and integrated into machining processes [5].

Although laser technology is widespread, but femtosecond lasers have not spread yet because the equipment usually had very low power. Nowadays also the equipment with sufficiently high power is available. Although less widespread in the industry, science is paying ever greater attention to technology, and more research and studies are being conducted on the subject. Femtosecond lasers deliver tremendous peak power. Because of the high peak power and short pulses, other physical phenomena occur when the laser interacts with the material, so the method of material removal is different from general lasers [6-7].
Compared to machining with nanosecond or longer pulses, drilling or cutting with femtosecond pulses does not result in melting. In the case of long pulses or continuous operation, we are essentially talking about thermal machining, which only works for materials that absorb the specific wavelength at which the laser operates. The process of laser ablation is related to the relaxation time of electrons in the case of metallic materials. The relaxation time can be between 1-10 ps for metallic materials. For longer pulses, the material completely melts in the irradiated area. This results in an uncontrolled flow of molten material, leading to the formation of irregular patterns.

However, it should be added that this phenomenon can be easily influenced and used to create patterns. If the duration of the pulses is less than the relaxation time that exists for femtosecond pulses, the material does not melt. Femtosecond laser radiation is accompanied by several phenomena, which depend on the working conditions, laser parameters and material properties.

Experience has shown that the ablation threshold can be reduced by as much as an order of magnitude for femtosecond pulses compared to nanosecond pulses, which allows for much more precisely controlled material separation, and the thermal impact zone can be minimized. This is why ultrashort pulses can be used to machine materials that conduct heat well. Experiments have also shown that the interaction of material and ultrashort laser pulses is a very complex phenomenon, which is also strongly influenced by the properties of the laser and the material. Furthermore, unlike nanosecond pulses, the thermal conduction of electrons can play an important role in the process of dissipating absorbed energy. However, at high power densities (above 1015 W/cm²) the benefits of ultrashort pulses may be lost. In such cases, a significant amount of melt can already be observed, and a significant temperature difference can cause either deformation arms or cracks [8].

When machining with ultrashort pulses, we can expect higher efficiencies at higher frequencies, since several pulses reach the surface in the same time interval. For example, if 1000 pulses are generated in 1 second, the frequency is 1 kHz, 50000 pulses in the same time is 50 kHz. However, the increased frequency also means smaller intervals between each pulse, resulting in two phenomena. This is one that less time is available for the propagation and distribution of heat until the arrival of the next pulse, which clearly influences the phenomenon of heat accumulation. The heat absorbed by the workpiece does not contribute to the material removal, but causes a splash around the hole, something re-solidified on the wall of the hole, which has a very negative effect on the quality of the hole. Another problem is that the removed material, which contains both liquid and gas phases, and the resulting plasma have less time to leave the treated area, which can also result in the accumulation of the removed material at the bottom of the created cavity. This can result in deflection and absorption of the laser beam, energy does not reach the bottom of the hole, the hole does not deepen further. From this it can be concluded that the repetition frequency significantly influences the process of micromachining, its result.

If the frequency is increased, exceeding the frequency of a few hundred kHz, the delay time between each pulse is shorter than the thermal relaxation time and therefore heat accumulation develops at the machined point, resulting in an increase in temperature. Increased temperature, in turn, results in a lower ablation threshold.

The burr along the edges of the hole is due to the accumulation of thin layers of molten material which adheres to it under the action of vapor pressure. From this it can be concluded that if this accumulation can be reduced, if the energy density is reduced, until it just exceeds the ablation limit. The disadvantage of this is that it greatly reduces the ablation rate. Furthermore, only very shallow shapes can be created at energy densities just above the ablation threshold. The minimum required energy density increases strongly with the depth of the hole. Experience has shown that spiral drilling, originally developed for nanosecond pulses, can be used in the femtosecond range as well. In the case of spiral drilling, the melt can also move sideways, which is later removed by a subsequent pulse, so it is not necessary to move axially and travel the relatively long way to the hole entrance to exit the hole, unlike impact drilling technology.

With these lasers, we have the ability to make machinations that have been expensive or complicated before. We have the ability to machining materials very accurate and precise. We can also work with
special materials such as stainless steel, aluminum, copper. In our study we investigated drilling with femtosecond laser on stainless steel [9].

2. Materials and Methods
In this paper we used stainless steel (AISI 304), one of the most common type of stainless steels. Machining stainless materials by other methods would be difficult, but very good results can be achieved with femtosecond laser. Before the laser machining, the surface of the steel was cleaned with methanol.

The laser drilling process was performed using a Coherent Monaco Femtosecond Laser with wavelength of 1035 nm. The laser impulses had 277 fs of width and the maximum average power was 40 W. The beam was focused on the surface with a diameter of 80 µm. There are properties that are given, we cannot change them. Such as the wavelength and modus of the laser beam. However, there are parameters that we can change within certain limits. Such parameters include frequency or pulse width. Another variable is the time of interaction between the material and the laser beam. There are several ways to control this: you can set how long the process lasts or how many laser pulses are received at a given point. The goal is to determine the parameters that can deliver the finest, highest quality material removal. We tried to find a setting where the material removal is as regular as possible, the heat affected zone is as small as possible.

Two setup strategies are used for the tests. In the first case the frequency was the fixed parameter (188 kHz and 50 MHz). These parameters are the extreme values of the frequency. The variable parameters were the laser average power (50 %– 100 %) and the number of pulses fired at one point (1 – 60000).

In the second case, the repetition number was set to a fixed value (10000) and the variable value was examined at 10 adjustable frequencies (188 kHz, 250 kHz, 330 kHz, 500 kHz, 750 kHz, 1 MHz, 2 MHz, 4 MHz, 10 MHz and 50 MHz) at different power levels.

For evaluation, the laser-drilled holes were examined under a microscope. The results were compared based on the hole and the heat affected zone diameter, as shown in the Figure 1.

![Figure 1. A) hole diameter measurement, B) heat affected zone diameter measurement](image)

3. Results
In the first case as expected, the amount of material removed increased as the number of pulses applied to the surface. Also, the diameter of the hole formed gradually increased as the pulse rate increased. The diameter of the craters also increased gradually as the pulse rate increased.

3.1. Results at 188 kHz
Along with these parameters, changes in the surface of the material were visible after a single pulse. As the number of pulses increases, more marked changes can be seen in the surface of the material. Already
after 4 pulses, it is noticeable that material has been removed in the treated area, and a crater has formed which is gradually increasing in depth. Figure 2 shows the hole diameter as a function of the number of pulses delivered to the surface at two power levels.

**Figure 2.** Hole diameter as a function of pulse rate at two power levels at 188 kHz

Overall, the hole diameters showing an upward trend. It can be observed that between 2 and 64 pulses the central diameter of the crater remains almost unchanged, typically around 70 μm, but from the recordings it appears that its depth increases slightly. Above the 2000 repetition number, the depth and geometry of the hole is such that we cannot see it with the help of a microscope. Between 4,000 and 15,000 iterations, stagnation is observed, with neither the hole nor the heat affected zone increasing significantly. Above this range, both diameter and heat affected zone show further increases. Figure 3 shows the evolution of the heat affected zone, which is similar to the change in hole diameter.

**Figure 3.** Changes in the size of the heat affected zone as a function of frequency at two power levels at 188 kHz
The diagrams show that there is little difference between the diameters of the holes created by the two laser parameters, but the difference in the heat affected zone is larger. From this it can be concluded that with less power more accurate material removal can be achieved.

3.2. Results at 50 MHz
Now examining material removal with the highest adjustable frequency. Because the maximum average power is given, in our case 40 watts, two important factors are significantly different from experiments at 188 kHz. One is the time elapsed between the two pulses, which is obviously much smaller at 50 MHz, and the other is the pulse energy, which is also significantly below the 188 kHz values. The two factors affect the properties of the hole in different ways. According to the literature, a smaller time interval between each pulse may result in greater heat accumulation, which may not only improve the efficiency of the process but also reduce the quality. In contrast, lower pulse energy can result in a more controllable process. Figure 4 below shows the evolution of hole diameter at 50 MHz at two different power levels.

![Figure 4](image_url)

**Figure 4.** Development of hole diameter as a function of pulse rate at two power levels at 50 MHz

If you look at the hole’s diameter, you can see that they are much smaller than the 188 kHz frequency. It is striking that after 256 pulses the laser has a noticeable effect, which is even smaller than at 188 kHz per pulse. The tendency is the same at the lower frequency, the hole and the heat affected zone increase with the increase of the pulse rate, but the size is much smaller than at the lower frequency. Figure 5 shows the evolution of the heat affected zone at the frequency of 50 MHz.
Although the quality of machining has improved, the heat affected zone is still significant. The results at 50% power are almost identical to those at 100% power. Apparently, there is no significant difference in quality or geometric properties. From the data it can be seen that with the two power levels, similar results were obtained, the diameter of the holes increased evenly throughout the range.

The above shows that the frequency has a great influence on the diameter and quality of the holes. The results clearly reflect the significant difference between pulse energies, at 188 kHz, even a single pulse left a trace larger than 256 pulses at 50 MHz.

3.3. Second treatment strategy
In the second phase, the effect of frequency was examined in more detail. In this case, the pulse number was not changed, it was 10,000 each time. The variable setting was power and frequency. Figure 6 shows the evolution of hole diameter as a function of frequency at three power levels.

Figure 6. The evolution of hole diameter as a function of frequency at three power levels
As expected, as the frequency increases, hole diameters typically decrease. When looking at 100% performance, it can be seen that the changes between 188 kHz and 500 kHz are almost negligible, and the hole diameter decreases very slightly. Then, at 500 kHz, the diameter begins to decrease sharply. At the same average power, peak power should theoretically increase with frequency decrease. That is, at 188 kHz, theoretically, much higher peak power is achieved, along with pulse energy.

If we examine the heat affected zone, similar processes can be observed. Figure 7 shows the evolution of the heat affected zone size as a function of frequency at three different power levels.

**Figure 7.** Size of the heat affected zone as a function of frequency at three power levels

In contrast to the hole diameter, which was constant between 188 kHz and 500 kHz at 100% power, the heat affected zone decreases with increasing frequency. This contradicts the expectation of the literature that an increase in frequency can cause heat congestion, which can increase the heat affected zone. The size of the heat affected zone alone carries little information without the size of the hole. More important is the size of the heat affected zone relative to the size of the hole. Figure 8 shows the size of the heat affected zone relative to the hole size.

**Figure 8.** Heat affected zone and hole diameter ratio as a function of frequency at three power levels
In this case, it is more difficult to talk about clear trends, the relative size of the heat affected zone seems to be less dependent on frequency. In addition to the different power levels, there was a minimum and maximum heat affected zone at different frequencies. In terms of proportions, the smallest thermal effect occurred at 50% power and 1 MHz, and the highest at 25% and 188 kHz. Performance affects the relative size of the heat affected zone. At almost all frequencies, 25% power produced the highest rate of heat effect, and in most cases, the deviation was very significant. The lowest rate of heat effect is typically 50%. The proportion of the laser beam's intensity distribution may also explain the higher proportion of heat effects. At lower power, only the central part of the beam has enough intensity to remove material, although the outer parts are subject to material changes, but material removal is not significant.

However, it is interesting that the decreasing power results in a larger heat affected zone, since the impulse energy decreasing due to the frequency typically results in a better quality end result and a smaller heat affected zone.

4. Conclusion

During our experiments it became clear that pulse energy plays a very important role in the process of material removal. Although in our case the frequency was the primary variable, but since each series was made with a constant average power, the change in frequency obviously brought about a change in the impulse energy.

The significant difference between the results of experiments at different frequencies is actually due to the pulse energy, but the effect of the frequency is not so significant. However, in the future, the effect of frequency alone should be investigated with constant pulse energy. The often mentioned advantage of femtosecond lasers is that no or only minimal heat effects are produced. With lower pulse energy, a clearly smaller heat affected zone was produced, and we think it is possible that even with a significant decrease in frequency we can achieve even better results.

In our research, we found that high pulse energy results in poor quality, but low pulse energy provides better control and more precise machining. We can produce a very high quality hole with 1MHz frequency, 50% power, 10,000 pulses, which has small heat affected zone.

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