A parametric study of sub-picosecond laser ablation of thin metal foils

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Abstract. With the properties of ultrashort pulse width and ultrahigh peak power, femtosecond lasers excel at processing materials whose thickness is less than 500 μm. Numerous experiments and theoretical analyses have testified to the fact that there are solid grounds for the future applications of femtosecond laser micromachining [1, 2]. However, with the high costs and complexity of these devices, it is the sub-picosecond laser that might be an alternative when it comes to micromachining of thin metal foils. Furthermore, investigating the sub-picosecond laser interactions with matter could provide a better understanding of the ablation mechanisms and experimental verification of existing models concerning the ultrashort pulse regime. We present research on sub-picosecond laser interaction with metal foils with a thickness of less than 250 μm under various laser pulse parameters. The research was conducted by two types of ultrafast lasers: a lab-designed sub-picosecond Yb:KYW laser (650 fs) and a commercial femtosecond Ti:S laser (35 fs). The results show how variables, such as pulse duration, energy, repetition rate, wavelength and irradiation time, affect the micromachining process.

1. Introduction
A scientific goal of this study is acquiring a better understanding of the ablation phenomena in a sub-picosecond regime. A practical goal is to provide arguments in favor of using sub-picosecond lasers as an alternative to femtosecond lasers in high-precision micromachining of metals. The ability of femtosecond lasers to process almost any material with negligible side effects and without the necessity of post-processing tools enabled the progress in the area of micro and nanotechnology. Still, the complex and difficult to calibrate femtosecond systems are considered unstable and not reliable enough for efficient commercial use [1]. The efficiency of the micromachining process depends, on the one hand, on the laser radiation parameters, such as pulse duration, wavelength, pulse energy, repetition rate or irradiation time, and on the other, on the target material properties [2]. These parameters affect the course of laser ablation. The nature of the ablation process in the femtosecond regime is different and more complex than that with longer, i.e. picosecond and nanosecond pulses [3-4]. We found that the region between picosecond and femtosecond laser pulses is interesting for further investigation, since both short and long pulse interactions with matter may take place. Most of the commercial femtosecond lasers offer pulse lengths of tens of femtoseconds. In our research, we used a popular 35-fs Ti:S laser and a 650-fs prototype Yb:KYW laser. Both provided adjustable wavelength (UV/VIS/IR) and repetition rate. The pulse energy ranges were picked so as to make the results of both lasers comparable to a maximal degree. This approach resulted in a complex parametric study, whereas previous research have mainly been focused on one or two selected parameters [2-5].
2. Experimental setup

The experiments were carried out using the two abovementioned lasers. The sub-picosecond Yb:KYW laser offers repetition rates of 100 – 400 kHz, power levels up to 15 W and the possibility of generating three different wavelengths in the UV, VIS, IR ranges, of which the wavelengths of 1030 nm and 345 nm were used for micromachining. The femtosecond Ti:S laser provides a repetition rate of 1 kHz and a wavelength tunable from 266 nm to 800 nm; we chose three wavelengths from this range.

Figure 1. Experimental setup for ultrafast laser micromachining.

From the laser output, the beam passes through an optical collimating and focusing system consisting of mirrors and lenses suitable for the laser wavelength applied. High-precision linear motors were used to move the sample in the XY plane [6]. The methodology and parameters of the experiments are presented in Table 1.

Table 1. Summary of the experimental conditions.

| Type of laser | Laser fluence \([J/cm^2]\) | Pulse energy \([\mu J]\) | Frequency \([kHz]\) | Scanning speed \([mm/s]\) | Wavelength \([nm]\) | Results |
|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| \(Yb:KYW\) 650 fs | 0.82-6.31 | 7.5-57.5 | 200 | 25 | 1030 | Figure 2 |
| \(Yb:KYW\) 650 fs | 3.16- | min. 28.75 @ 400 kHz | 200 | 25 | 1030 | Figure 3 |
| \(Yb:KYW\) 650 fs | 12.63 | max. 115 @ 100 kHz | 200 | 25 | 1030 | Figure 3 |
| \(Ti:S\) 35 fs | 3.02 | 27.5 | 200 | 0.7-13 | 345 | Figure 4 |
| \(Yb:KYW\) 650 fs | 3.02 | 27.5 | 200 | 13-50 | 266 | Figure 4 |
| \(Ti:S\) 35 fs | 2.8 | 40 | 1 | 25 | 266+532+800 | Figure 5 |

3. Results

The ablation mechanisms depend on the laser radiation parameters – pulse duration, wavelength, pulse energy, repetition rate, and on the material properties – absorption coefficient or thermal conductivity [2]. In laser-irradiated samples, various features, such as crater dimensions, local changes in crystallography and chemistry, surface modification, can be related to various dynamical mechanisms and the ablation threshold. A Nikon Eclipse microscope was used to measure the post-machining craters dimensions and the heat-affected zone on the surface of each sample. Representative results are presented below (Figures 3-5).
Figure 2 presents six types of metal samples machined with the sub-picosecond laser. Each 1-cm line was scribed with a different laser pulse energy. It was seen that the crater width decreased as the energy was decreased. The microscopic analysis showed the lack of visible effects in the heat-affected zone and of debris on the surface, even for energies much higher than the ablation threshold. The line edges were straight and clean, except for energies exceeding 37.5 µJ. The best results were obtained for energies within the range 7.5 – 17.5 µJ. All samples were machined at a scanning speed of 25 mm/s.

Figure 2. Numerical results of laser micromachining of metals with variable pulse energy.

Figure 3 shows how the crater width decreased as the sub-picosecond laser repetition was increased. The methodology and materials were the same as in the precious experiment. Although a higher repetition rate results in a tighter overlapping of the laser pulses, the pulse energy decreases, resulting in a thinner line. However, varying the repetition rate strongly affected the crater profile, which was not the case when only the pulse energy was varied.

Figure 3. Numerical results of laser micromachining of metals with variables repetition rate.
Figure 4 shows results of micromachining of three different types of metal samples using the two lasers (Ti:S 35 fs and Yb:KYW 650 fs). A series of lines were scribed at different scanning speeds. It was seen that the crater diameter increased as the scanning speed was decreased, but the depth of the crater was not significantly affected. A higher micromachining speed means less time for laser-matter interaction and heat transfer. An optimal speed must be determined for each material depending on its parameters. This was especially evident with copper, which has a higher specific heat than the other materials examined. For shorter pulses, faster micromachining rates were applied. The material of the samples seemed to be less affected by the scanning speed in the femtosecond regime, but more so in the sub-picosecond regime.

Figure 4. Numerical results of laser micromachining of metals at variable scanning speed.

Both lasers provided wavelength choices in the IR, VIS, UV ranges. Certain wavelengths work best for specific materials. One can select the wavelength based on a particular feature size required, e.g., the smallest focus spot size achievable is directly related to the wavelength. The arguments in support of matching different wavelengths to different materials are less obvious for shorter pulses. The normal material absorption dependency on the wavelength would no longer apply due to the nonlinear absorption dominating in an ultrashort pulse regime [7].

Figure 5 presents the results obtained by the Yb:KYW laser at a pulse width of 650 fs and by the Ti:S with a 35-fs pulse width using different wavelengths. In both cases, a 1-cm line was scribed on each sample for every wavelength available. The effect of the wavelength change was different. For example, in aluminium, the material reflectivity increases with the increasing wavelength. The UV range is considered most suitable for precise micromachining for most metals. This effect was confirmed for the Yb:KYW sub-picosecond laser, where the UV beam was absorbed well, but not for the femtosecond Ti:S laser. Machining by a 266-nm and an 800-nm beam resulted in a similar crater width. For both lasers, laser light in the VIS range was poorly absorbed by the aluminum sample; however, a better absorption was observed in the cases of shorter pulses.

As a reference, the theoretical ablation thresholds for metals were calculated using the solution of eq. (1) as proposed by Gamaly et al. [8]. The effects of the laser pulse parameters on the ablation threshold, heat accumulation, ablation efficiency, cold and hot ablation mechanisms and the amount of liquid phase occurring during the laser irradiation were studied for each material. The specific material parameters, like absorption rate or heat conductivity are included as a significant variables.

\[ F_{th} = \frac{3}{8} (\varepsilon_b + \varepsilon_{esc}) \frac{\lambda \eta_a}{2\eta} \]  

(1)
In most cases, the ablation thresholds calculated were higher than the experimental values. The predictions were better in the case of the sub-picosecond laser.

Figure 5. Numerical results of laser micromachining of metals at different wavelengths.

4. Conclusions
While both the craters’ width and depth increased with the laser fluence, the increase of the heat affected zone was small or non-existent in the sub-picosecond regime. Equation (1) proposed for estimating the ablation threshold can be applied to both (femto and sub-picosecond) cases, with better results in the sub-picosecond regime. The influence of the laser wavelength is less significant in the femtosecond regime than it is in sub-picosecond one. This is possibly due to the involvement of non-linear absorption mechanisms (i.e. multiphoton absorption) occurring during ultrashort laser pulses. However, in our study we focused on the macroscopic results of the laser-matter interactions, without considering the specific heat transfer mechanisms. A comprehensive study on the complicated nature of electron and plasma behavior in ultrashort regime can be found in [1,2,7]. The aim of this research was to present the sub-picosecond (650 fs) laser as an adequate alternative to the femtosecond laser (35 fs) in the high-precision micromachining of metals. Considering the abovementioned findings, a sub-picosecond laser will allow one to control more accurately the micromachining process parameters thus achieving more predictable results. The results reported will facilitate the identification of some ablation mechanisms in the sub-picosecond regime and show their dependence on the laser pulse parameters. Therefore, they will enable one to verify the existing models and theories and increase the cost-efficient applicability of ultrafast lasers in micro and nanomachining.

References
[1] Neuenschwander B, Bucher G, Hennig G, Nussbaum C, Joss B, Muralt M, Zehnder S, Hunziker U and Schütz P 2010 Proc. International Congress on Applications of Lasers & Electro-Optics 2010:1 707-715
[2] Liu X, Du D and Mourou G 1997 IEEE J. Quantum Electron. 33 1706
[3] Anisimov S, Inogamov N, Oparin A, Rethfeld B, Yabe T, Ogawa M and Fortov V 1999 Appl. Phys. A 69 617
[4] Kramer T, Remund S, Jäggi B, Schmid M and Neuenschwander B 2018 Adv. Opt. Technol. 7 3
[5] Peterlongo A, Miotello A and Kelly R 1994 Phys. Rev. E 50 4716
[6] Garasz K, Kocik M and Petrov T 2019 J. Phys.: Conf. Ser. 1186 012028
[7] Dyukin R, Martsinovskiy G, Sergaeva O, Shandybina G, Svirina V and Yakovlev E 2012 Interaction of Femtosecond Laser Pulses with Solids: Electron/Phonon/Plasmon Dynamics, \textit{Laser Pulses - Theory, Technology, and Applications}

[8] Gamaly E, Rode A, Tikhonchuk V and Luther-Davies B 2002 \textit{Phys. of Plasmas} \textbf{9} 949