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Use of bursts for femtosecond ablation efficiency increase

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Abstract

The challenge of ultrafast processing is to increase throughput for applications in industrial production. The laser burst mode is identified as a method increasing the throughput in fs-processing applications by a higher ablation efficiency. In this context highly controlled burst is a key function for femtosecond lasers. The architecture of femtosecond laser allows to generate bursts with user defined number of sub pulses and energy shapes over a wide range. In this work, we show how to optimize processing parameters in order to maximize the ablation efficiency and avoid detrimental thermal effects. In particular, the role of energy distribution in sub pulses will be highlighted, showing the possibility of increasing effective pulse energy by a factor up to 5, with a precise control of corresponding consequences for ablation results in cutting or surfacing. Simulation tool for a quick estimation of suited parameters will be also presented.

Keywords: Bursts of femtosecond pulses, femtosecond processing, ultrafast ablation

1. Introduction

The name "burst" can cover several different types of achievements, but in general, it means to use a train of a few pulses rather than one, with a repetition rate between the pulses of the train much higher than the repetition rate of the burst itself. For the lasers whose architecture is based on a selection of pulses to be amplified (pulse picking), it is possible to use the pulse trains at the repetition rate of the oscillator (40 MHz in the case of lasers used for this work) with the usual repetition rates of the lasers (hundreds of kHz). The effect of a burst is therefore a modification of the temporal sequence of addressing the energy available to the material. From a laser technology point of view, the use of a burst mode can be limited in repetition rate, because the amplification can induce changes in energy and pulse duration of the burst pulses as their number increases. Solutions exist to manage the shape of the bursts and are now also proposed to optimize the process [Hoenninger *et. al.* 2018]. In addition, new technological approaches make it possible to obtain pulse trains at repetition rates higher than MHz (GHz or THz), involving new ablation mechanisms and a

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significant increase in ablation efficiency. We will focus in this work on the case of the MHz burst, accessible to most femtosecond laser technologies currently used.

The ablation efficiency depends of course on the response of the material to this change of the temporal sequence of pulses. This material response is never linear, so simple proportionality rules are not usable. To try to clarify different aspects of the interest of burst for ablation, we will first distinguish two types of physical mechanisms

2. Simplified description of the ablation mechanism.

A simplified description of the response of the material to a femtosecond pulse is often used, based on the assumption that the ablation depth z depends on two characteristic parameters of the material δ and F_{th} according to

$$z = \delta \ln \frac{2F_p}{F_{th}} \qquad (1)$$

Where F_p is the average fluence of the considered pulse and $E_p = \pi \omega_0^2 Fp$ its energy. In the case of a Gaussian laser pulse, the ablated volume by this pulse is then given [see for instance Audouard *et. al.* 2016] by:

$$V = \frac{\pi \omega_0^2 \delta}{4} \ln^2 \frac{2F_p}{F_{th}} \qquad (2)$$

Where ω_0 is the waist of the beam.

2.1 Specific interaction mechanisms.

The use of bursts has led to many works [Kramer *et. al.* 2017, Jaeggi *et. al.* 2018]. Specific physical mechanisms have been evidenced. The role of a pulse-to-pulse thermal accumulation has been widely demonstrated, as a phenomenon either beneficial if one considers its contribution to an increase in ablation efficiency or limiting if we consider the possible degradation of the machining quality due to these thermal effects. Other limiting or beneficial mechanisms are also studied such as shielding effects [Foerster *et. al.* 2018] or the increase the surface roughness [Neuenschwander *et. al.* 2019]. These mechanisms are obviously to be taken into account for the expertise of a particular process. For the following, we consider only the simplified description of abaltion to evaluate different burst achievements, without claiming a prediction of the experimental results. In the following, we consider MHz burst (typically 40 MHz, time between two pulses 25ns) with a burst number from 1 to 10, for a laser rate of 100 kHz.

2.2 Description of evolution of efficiency with fluence

We evaluate the use of a burst with a beam motion characterized by a speed v_s. The repetition rate f of the laser and v_s define the spacing between two spots of a diameter d.

The spot overlap $R = 1 - \frac{v_s}{d.f}$ characterizes the experimental configuration used. For cutting applications the value of R is typically 0.7, and rather 0.9 in the case of surfacing.

In the context of the simplified description presented above, an analytical calculation [Audouard et al. 2016] allow to estimate the ablation rate D with a very simple expression:

$$D = V.f = f.k\ln^2 F \qquad (3)$$

For simplification, we write $k = \frac{\pi\omega_0^2\delta}{4}$ and $F = \frac{2Fp}{Fth}$

To evaluate the efficiency of a pulse as a function of fluence, a specific quantity is usually calculated, for example $e_f = \frac{D}{P}$ where P is the total target power.

According to the previous expressions, it comes

$$e_f = f.\frac{k}{P}\ln^2 F \qquad (4)$$

In the general case of a burst composed of N pulses with the same energy E_p, we consider the response of the material to N separate pulses, but delivering a total power $= N.E_p.f$. Equations (3) and (4) are then written

$$D = N.f.k\ln^2 F \qquad (3b)$$

$$e_f = N.f.\frac{k}{P}\ln^2 F = \frac{\delta}{2Fth}.\frac{1}{F}\ln^2 F \qquad (4b)$$

These last two equations highlight several behaviors typical of the use of the burst mode:

- The ablation rate is increased in the same ratio as the number of pulses in the burst. Equation (3b) shows that an increase in repetition rate f would lead to the same result. The increase of ablation rate by the increase of the repetition rate or by the burst mode is therefore similar and is done in both cases for the same increase of average power addressed to the material. This potential increase in ablation rate is therefore related to the possible increase of the laser average power.
- On the other hand, the ablation efficiency is independent of N and of f. The use of a burst therefore does not generally lead to an increase in ablation efficiency nor more than the repetition rate increase.

We can draw a first conclusion from the points mentioned above. Apart from the possible contributions of burst-specific ablation mechanisms, there is no advantage to use a burst of N pulses at the same pulse energy, rather than an increase in repetition rate, to translate larger available laser power into higher productivity. This conclusion must however be reviewed according to the practical conditions of experimental implementation. Indeed, an increase in productivity by increasing the repetition rate often requires adapting the chosen movement speed v_s to maintain a constant pulse overlap R in order to maintain the same controlled process. This increase in speed is most often based on the use of mechanical tools (scanners, translation plates) that may have limitations in their ability to provide high speeds v_s. The use of a burst can eliminate this limitation by using high average power without having to accelerate the process.

3. Burst with constant total energy.

Equation (4b), however, underlines a burst specific behavior if one has to compare a single pulse having an energy different from that of the individual pulses of the burst (cf. figure 1). We consider for example the case of a burst whose burst total energy is equal to the energy of the single pulse.

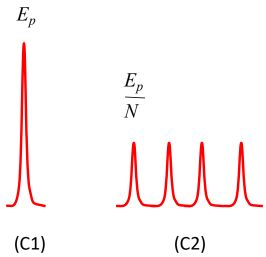

Fig. 1: burst with conservation of the total energy of the corresponding mono pulse

The factor $\frac{1}{F}\ln^2 F$ in equation (4b) shows a maximum value, obtained for $F_{opt} = \frac{e^2}{2} F_{th}$ which indicates a fluence value with a maximum efficiency. Since the threshold fluences of metals are generally quite low, this optimal fluence is therefore also low and rarely used for a process. For stainless steel, we can estimate F_{th} at 0.1 J/cm^2, and the optimal fluence is around 0.5 J/cm^2. The burst (C2) with respect to the single pulse (C1) performs ablation with lower pulse energies but in a fluence domain where these sub pulses are more efficient.

To evaluate the efficiency of these two options, let's write equations (4) in these two cases, considering that the repetition rate is constant. For the case (C1), we therefore consider a reduced fluence pulse F and power $P = E_p.f$, in the case (C2) a train of N pulse of the same total power P. It comes

$$e_f = f.\frac{k}{P}\ln^2 F = \frac{\delta}{2Fth}.\frac{1}{F}\ln^2 F \qquad \text{(4-C1)}$$

$$e_f = N.f.\frac{k}{P}\ln^2 \frac{F}{N} = \frac{\delta}{2Fth}.\frac{N}{F}\ln^2 \frac{F}{N} \qquad \text{(4-C2)}$$

Figure 2 shows the calculation of $\frac{1}{F}\ln^2 F$ and $\frac{N}{F}\ln^2 F$ factors for N = 3,5,10, and in the case F_{th} =0.1 J/cm^2. It is thus possible to compare the expected differences in efficiency between (C2) and (C1).

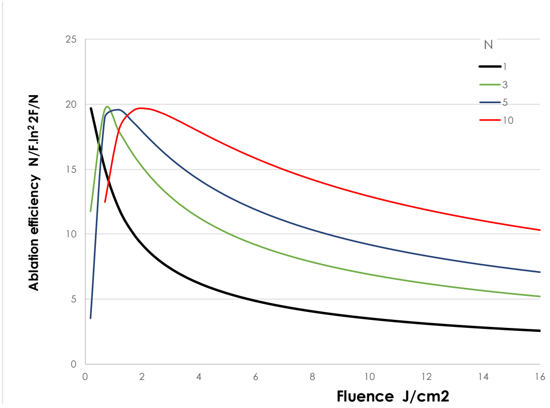

Figure 2: Calculation of the factor of efficiency (see text) of a single pulse (N=1) and a burst (N=3,5,10) of the same total energy.

Whatever the case, the maximum efficiency obtained is the same, which is in line with the previous conclusions. But this maximum is not reached for the same values of fluences. This means that depending on the fluence domain considered, the differences in efficiency can be significant. For fluences that are close to the threshold fluence, the single pulse can lead to efficiencies greater than that of the bursts. For higher fluences the burst leads to greater efficiencies. The phenomenon is accentuated with the increase in the number of pulses: area of low efficiency is more important in the low fluences, but higher efficiencies are reached for the higher fluences. Note, however, that the field of high fluences is generally more favorable to the thermal effects mentioned above and the trends given by these results must be confronted with the experiment to be confirmed.

4. Confrontation with experimental results

Figure 4 shows experimental results obtained in the case of stainless steel using a TANGOR type laser, used at a low power range also accessible to a SATSUMA type laser.

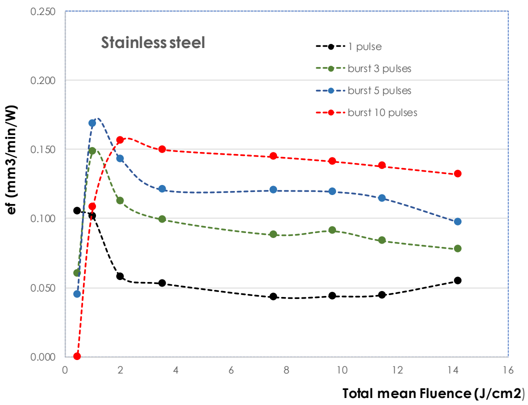

Figure 3: Measurements of the efficiency of a single pulse and burst of the same total energy (3.5.10 pulses per burst).

The repetition rate is fixed at 100 kHz. The spot size on the sample is 50 µm. Cavities are made using a scanner (scan speed of 1.5 m / s) leading to a recovery of 70%. The distance between lines for the realization of the cavities is l = 15 µm, they are made by scanning in a single direction, with np = 100 passages to obtain a sufficient precision of the depth measurement (prof). From this depth measurement, we deduce the experimental value of the efficiency

$$e_f = \frac{f.prof.l^2}{np.P}$$

For a given value of the single pulse energy, the laser is set in "burst mode N", generating a train of N pulses of the same energy E_p, each sub-pulse thus having an energy of E_p / N.

The experimental values in Figure 3 cannot be exactly adjusted to calculated values in Figure 2, but they do show the expected trend. The field of low fluences (less than 2 J/cm^2) is not described with enough experimental points to visualize the behaviors more finely between the different cases. In the case of high fluences, the increase in efficiency as a function of the number of pulses in the burst is clearly highlighted. The decrease in efficiency expected at high fluence is not visible, probably because of a contribution of thermal effects, which is confirmed by the observation of the surface qualities of the cavities produced.

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