Application of picosecond lasers for surface modification and polishing

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Abstract: This paper examines the interaction of 100 ps laser pulses in pseudo-continuous lasing mode on SS 304 Stainless steel. Theoretical models for picosecond interactions are examined and qualitative explanations of material response experiments are presented. Finally, we demonstrate surface polishing of SS 304 stainless steel targets.

1. Introduction

There has been a startling acceleration in the development of industrial Laser sources in recent years. Fiber and disc lasers have led the way, improving beam quality to the diffraction limit, while at the same time increasing the available power. Current market size for industrial material processing lasers stand at over €6Bn per year with laser cutting, drilling, micro processing and marking comprising the majority of the share within the Automotive, Aerospace and Semiconductor industries. As of 2010, this accounted for some 70% of the overall market units sold worldwide. Real world applications are pushing the development of high repetition rate, high beam quality, high average power ultrafast fiber lasers. Over the past decade availability of nanosecond sources has stimulated study in the field. The next natural choice for study, namely low nanosecond and picosecond interaction regimes, remains largely unexplored. The introduction of high performance short-pulse systems such as fiber and DPSS lasers with repetition rates in the several hundred-kHz range, have provided the user with a wide range of interaction parameters to chose from. However, understanding the fundamental mechanisms governing light matter interaction needs to be further studied to enable precise control of material responses for precision material processing. In this paper we present surface modification and surface polishing of SS 304 stainless steel targets using picosecond lasers operating at high repetition rates 7.2 MHz, and high pulse energies (max 2.08 μJ).

2. Theory

Material absorption plays an important role in laser machining. Material absorption is a complex mechanism and depends on the temperature of the sample T, laser wavelength λ and the rate of energy deposition. As such, most materials cannot be assumed to have steady state absorption under arbitrary laser light and a dynamic model is required. The timescales of physical mechanisms associated with picosecond pulse interaction with matter [1,2] is given in Figure 1.

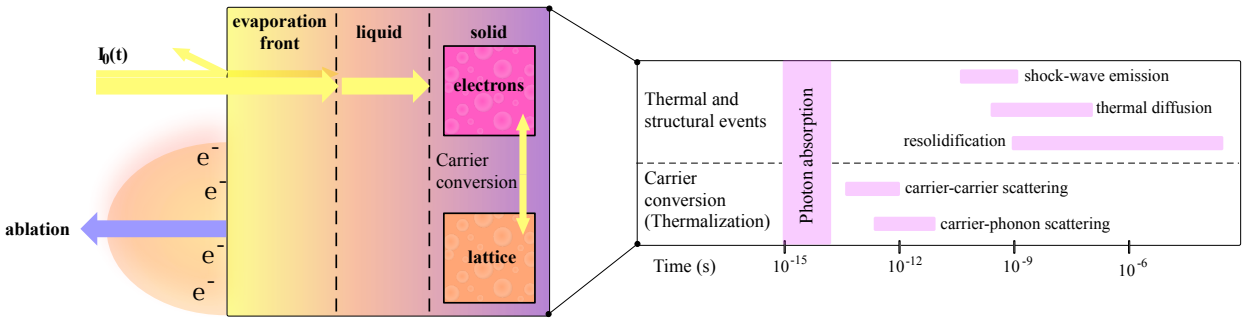

Figure 1: Timescales and the physical mechanisms associated with picosecond pulse interaction with matter.

In the nanosecond regime, the dynamics of the system can be characterized by the electron temperature T_e, electron cooling time τ_e, the lattice temperature T_i, and the lattice heating time τ_i using the 1-D thermal diffusion model [1,3]:

$$\tau_e \gamma \frac{\partial T_e}{\partial t} = k_e \frac{\partial^2 T_e(z)}{\partial z^2} - \xi(T_e, T_i) + S(T,t) \quad (1)$$

$$\tau_i \gamma \frac{\partial T_i}{\partial t} = \xi(T_e, T_i) \quad (2)$$

where (1) and (2) are related by $\xi(T_e, T_i) = \gamma(T_e - T_i)$, k_e is the electron thermal conductivity and γ characterizes the carrier-phonon coupling. $S(T,t)$ is the energy absorbed by the sample (or the source term) and can be described by

$$S(T,t,\lambda) = AI(t)\alpha(T,\lambda)e^{-\alpha(T,\lambda)z} \quad (3)$$

where $A = (1 - R - T_\lambda)$ and R and T_λ are the reflected and transmitted components of the temporal pulse profile $I(t)$, α is the material absorption coefficient for incident laser wavelength λ, and z is the distance inside the sample normal to the surface. Finally, the source term $S(T,t,\lambda)$ implies a relationship with the laser pulse duration τ_L that determines the regime conditions. In the case of picosecond pulses, the pulse duration is much shorter that the lattice heating time such that the condition $\tau_e \ll \tau_L \ll \tau_i$ is satisfied so that the lattice temperature is always smaller than the electron temperature. In this case at a time t [1]:

$$T_i \sim \frac{t}{\tau_i} T_e \quad (4)$$

This implies that thermal diffusion will occur within the timeframe of the pulse assuming that the source term $S(T,t,\lambda)$ does not exceed a certain threshold fluence level F_{th}. If these conditions are met it is possible to approach a quasi-continuous regime whereby the material experiences rapid heating and cooling *without* ablating the material.

3. Experimental

The set up of the test rig is shown in Figure 2. The sample is placed on moveable lab jack and the position relative to the scan lens focal length is measured using a dial gauge. The lens used is a Jenoptik™, model 03-90FT-125-1064, focal length 125mm, scan area 90mm x 90mm scan field and is telecentric to within 5 degrees deviation from normal. The scan head is a Nutfield™ 1064nm XLR8-15-1064 x-y head with an optical input aperture of 15mm. The tests were carried out using the Nutfield™ Waverunner software, which was also used to design the test pattern.

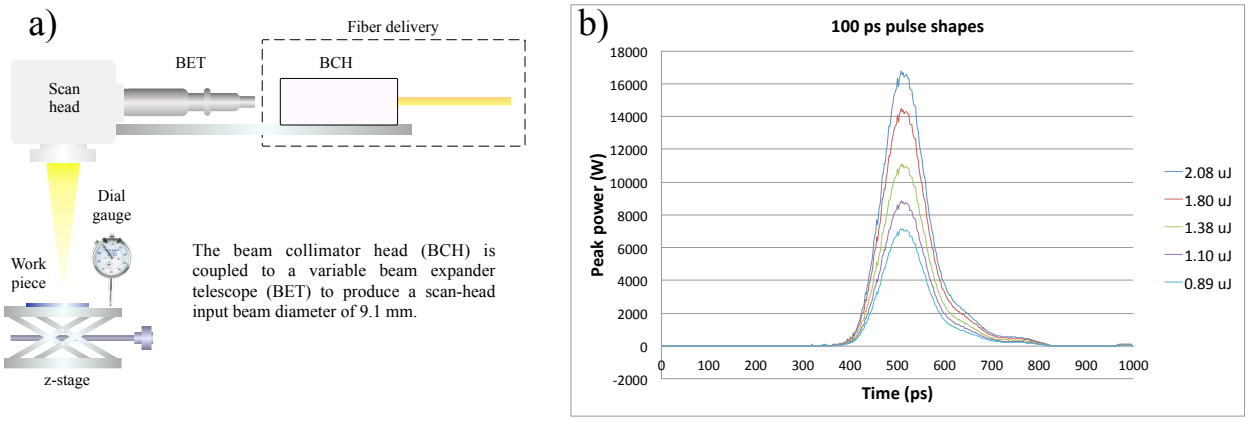

Figure 2: a) The test rig and b) the pulse shapes and peak powers for a range of pulse energies from E_{pulse} = 0.89 μJ – 2.08 μJ.

The system is a fiberized YDFA MOPA with an output beam of M^2 = 1.1 with a power output exceeding 100 W. The minimum spot size achievable using our set up is d_{min} = 21 μm. More about the system can be read in [4,5]. Spot overlap on the sample was determined to be 99.5% in the direction of machining (separation of 0.138 μm) and the temporal pulse separation 138 ns. A series of experiments were carried out to determine the effect of a variety of energy deposition profiles on the material responses.

4. Results

Figures 3 and 4 show the material responses of SS 304 using a range of pulse energies E_{pulse} = 0.89 μJ – 2.08 μJ. There are three surface morphologies that are observed. For energies below E_{pulse} ~ 1.00 μJ the surface is lightly perturbed and surface periodic surface structures are evident in some areas. For energies above E_{pulse} ~ 1.05 μJ a clear zone of remelting is evident, which amounts to a dramatic reduction in surface roughness, compared to the large grain structure of the cold worked stainless steel surface, (see Figure 3 b-d). The optical penetration depth for 1064 nm radiation on steel is of the order of a few nanometres so the absorption $\alpha(T,\lambda)e^{-\alpha(T,\lambda)z}$ in the source term in (1) decays quickly and only the very top layer is initially melted. This causes a temperature gradient both into the sample (z-direction) as well as radially from the center of the line (due to a Gaussian intensity profile of the laser spot). The lateral thermal gradient causes a contraction of the molten surface layer away from the centre. At energies above E_{pulse} ~ 1.38 μJ it recedes to the edges of the machined line as can be seen in Figure 3 e-h.

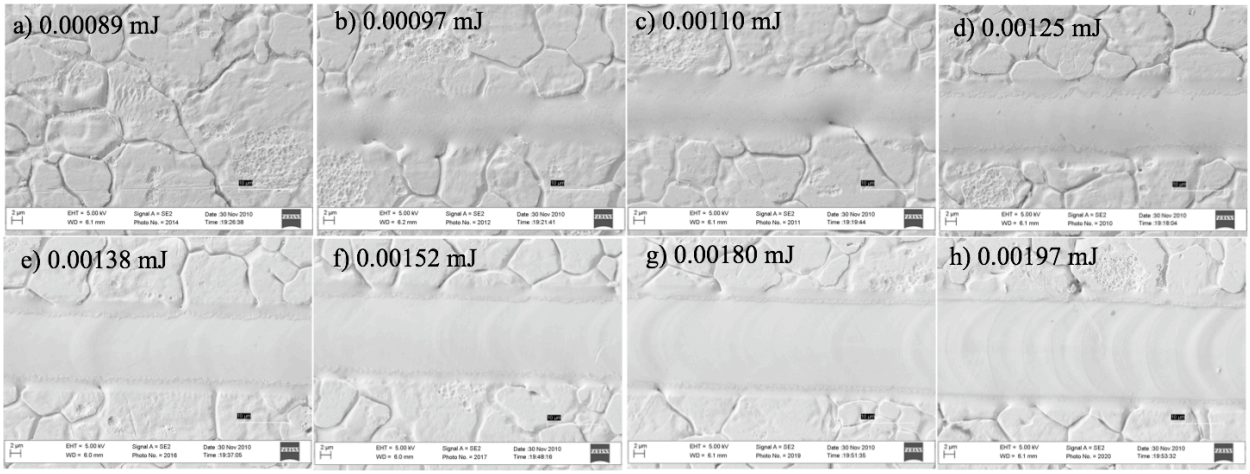

Figure 3: Shows SEM (Zeiss™ 1640 crossbeam) images of material responses of SS 304 stainless steel using 100 ps pulses with a range of pulse energies of E_{pulse} = 0.89 μJ – 1.97 μJ.

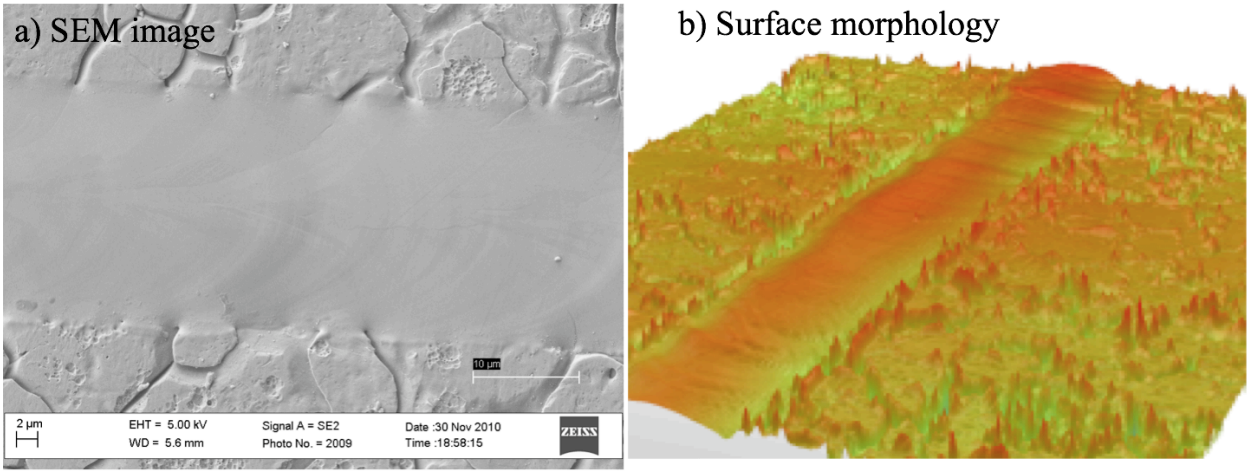

Figure 4: a) Shows SEM image of SS 304 stainless steel using 100 ps pulses with a pulse energy of E_{pulse} = 2.08 μJ and b) the surface morphology (Veeco™ NT3300 white light interferometer).

For energies above E_{pulse} = 2.08 μJ full melting occurs across the spatial profile of the laser (see Figure 4 a). The first pulse melts the material that is partially molten with thermal diffusion into the material occurring well before the subsequent pulses arrive. This energy deposition profile allows the material to partially resolidify and settle, within the duty cycle of the laser creating a fine structured "polished" surface.

5. Conclusions

We have demonstrated that picosecond lasers operating at high repetition rates 7.2 MHz, and high pulse energies (max 2.08 μJ), can produce fine remelting zones on the surface of 304 stainless steel. Theoretical models for picosecond interactions are examined showing that the energy deposition profile is key for fine structuring applications, with a very narrow parameter window. Qualitative explanations of material response experiments are presented and it is suggested that surface tension is the dominant mechanism responsible for the observed surface morphology particularly at lower pulse energies. For higher energies (> 1μJ) we demonstrate surface polishing of SS 304 stainless steel targets. We envision that potential applications could include the creation of ultra smooth substrates with fine grain microstructures, for applications in laser surface alloying, wear reduction through lower coefficient of friction, and enhanced corrosion resistance. Further work is necessary to explore the microstructural changes induced by high-repetition rate ps lasers.

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6. References

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