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Effect of the pulse duration on the surface roughness and the heat affected zone in laser micro polishing processes

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Abstract

Micro polishing of metal surfaces by means of pulsed laser has attracted increased interest in the last decade, especially due to the precision it offers and the absence of waste byproducts in relation to traditional mechanical abrasive methods. The process for micro laser polishing requires melting a thin surface layer in order to reduce the roughness by means of the surface tension of the melt pool. This in turn produces a heat affected zone beneath the melted layer. In applications where the structural properties of the material must remain unchanged, the depth of the melted layer plus the heat affected zone have to be tightly controlled. One of the most important parameters that conditions both the maximum affected spatial period of the surface roughness (which increases the efficiency of the process) and the maximum thermally affected depth is the pulse duration. In this work the authors have studied the effects in these magnitudes as a function of the pulse duration between 20 and 200 ns. This has been done with a variable pulse laser of a wavelength of 1064 nm over an iron and nickel alloy, scanning the surface with a fixed frequency of 5 kHz. In the case of the evaluation of the surface roughness, a frequency-domain spectral analysis of the images has been performed to study the effect of the pulse duration on the frequency spectrum of the surface roughness. Considering the half width at half maximum (HWHM) of the frequency-domain spectral content of the images, the results show a gradual decrease of the minimum affected frequency of the surface roughness down to 0.21 μm^{-1} (which corresponds to a spatial period of 4.76 micrometers). This means that the process can erase surface features with a maximum width of 4.76 micrometers. In the case of the depth

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of the heat affected zone (plus the melted layer), a range of 1.5 to 4.5 µm was measured for pulse widths between 20 and 200 nanoseconds.

Keywords: laser micro polishing; nanosecond laser; FFT analysis

1. Introduction

The possibility of resorting to a laser solution for the polishing of different materials such as silica rods, diamond surfaces [Shafeev et al., 1995; Erdemir et al., 1997], or fused silica or quartz lenses [Gloor et al., 1999], has been widely addressed in literature and used in industrial systems. The polishing of metals, although already studied by Tuckerman and Wiesberg, 1986 and Marella et al., 1989 for thin films, has been only recently started to be used in industrial applications for metal parts [Mai and Lim, 2004; Shao et al., 2005; Lamikiz et al., 2007].

The main advantages of using a laser source instead of a mechanical procedure are the lack of waste byproducts and the precision it offers. The parameters that define the final result obtained with this type of process are the initial surface roughness and the type of laser source. As the laser polishing process is based on the melting of the surface layer of the material, the pulse duration has to be carefully chosen to obtain a melt pool with a defined depth while, at the same time, avoiding any ablation. As stated by Perry et al., 2009, the geometries present in the surface will smooth out in a decaying sinusoidal manner under the influence of the surface tension and the viscosity, when the area on which they are located is melted. Fourier components are used to model these geometries existing on the surface, and the evolution of the shape of the surface with the time can be studied predicting the behavior of each of the components. According to Landau and Lifshitz, 1959, for capillary waves of wave number κ, in a liquid with depth h and where the amplitude to wavelength ratio is small, the damping time τ is represented by the equation (1).

$$\tau = \frac{\rho}{2\mu\kappa^2} \tag{1}$$

In the above equation, ρ is the density and μ is the dynamic viscosity. The wave number is inversely proportional to the wavelength (2):

$$\kappa = \frac{2\pi}{\lambda} \tag{2}$$

According to both expressions, the longer the wavelength the more time it will take for a capillary wave to dampen. If each Fourier component is equated to a wave of this type, then the melt duration will be the key factor to know which is the biggest geometrical feature affected (in terms of spatial period) by the laser polishing process. As the melt duration is determined by the pulse duration, for a given laser wavelength this parameter will define the minimum achievable roughness in the process (alongside the initial state of the surface).

Taking into account the relation of the pulse duration with the final roughness, it might follows that the longer the pulse the more effective polishing process. Although this is true for the materials and applications where the roughness is the only important parameter, in applications where the structural properties of the bulk material must be kept the heat affected zone beneath the surface must be kept to a minimum depth. According to Mai and Lim, 2004 the thermal penetration depth L_{th}, in which the heat affected zone is included, increases with the pulse duration:

$$L_{th} = 2\sqrt{k \cdot t_p} \quad (3)$$

where

$$k = \frac{K}{\rho \cdot c_p} \quad (4)$$

As expressed by the equation (3) the thermal penetration also depends on the thermal diffusivity k, which in turn depends on the thermal conductivity K, density ρ and specific heat capacity c_p of each material.

As a result, for applications where the heat affected zone has to be contained, a compromise between the maximum reduction of the roughness and the maximum thermally affected depth must be found.

2. Experimental setup

In this work the authors have studied the variation of the surface roughness and the heat affected zone with the pulse duration in a 50% nickel-iron alloy. This type of alloy is used for a variety of applications such as LF power transducers, rotor and stator laminations, chokes, relay parts, integrating current transformers for earth-leakage, circuit breakers, stepping motors, shieldings, etc. A fiber laser that generates a near Gaussian beam with a M^2 of 1.35 at different pulse durations and at a wavelength of 1064 nm has been used. The preset pulse durations are 10, 20, 30, 50, 75, 100, 150 and 200 ns. It can work in a constant peak power region up to 18 kHz at 200 ns, and in a constant average power region up to 250 kHz at the same pulse duration. For these tests, a frequency of 5 kHz has been set to maintain the peak power constant. The scanning of the surface of the samples has been performed using a precision 3-axis stage, allowing for a 95% of overlapping between pulses. The samples are cylinders 2mm thick with a diameter of 7.96 mm and a center hole of 2.5 mm. The samples used to study the effect on the surface have been only half processed, whereas for the characterization of the heat affected zone the surface of the samples has been totally scanned by the laser. The laser has an initial 640 μm diameter spot which has been focused through a 50.8 mm diameter lens with a focal length of 100 mm. In order to avoid surface oxidation, a chamber equipped with a window and filled with argon gas has been used to process the samples.

The analysis has been made using a scanning electron microscope (SEM) with a resolution of 3.5 nm at 30 kV. To confirm the increase of the maximum affected spatial period with the increase of the pulse duration a frequency-domain spectral analysis of the images has been performed. To study the heat affected zone, samples have been cut perpendicularly to the laser treated surface before being inspected in the SEM.

3. Results and discussion

To produce the surface melting needed for laser polishing without ablation, a power of 700mW has been chosen according to preliminary tests performed by the authors, in which partially mechanically polished samples of the same material were processed at 200 nanoseconds with different power levels. As the principal goal of the study is to analyze the influence of the pulse duration, the aforementioned value has been maintained at all pulse durations except for the lowest ones (10, 20 and 30 ns). At this pulse durations the maximum power levels provided by the laser were used, which are 670 mW for 30 ns, 390 mW for 20 ns and 150 mW for 10 ns.

3.1. Influence of the pulse duration in the maximum affected spatial period

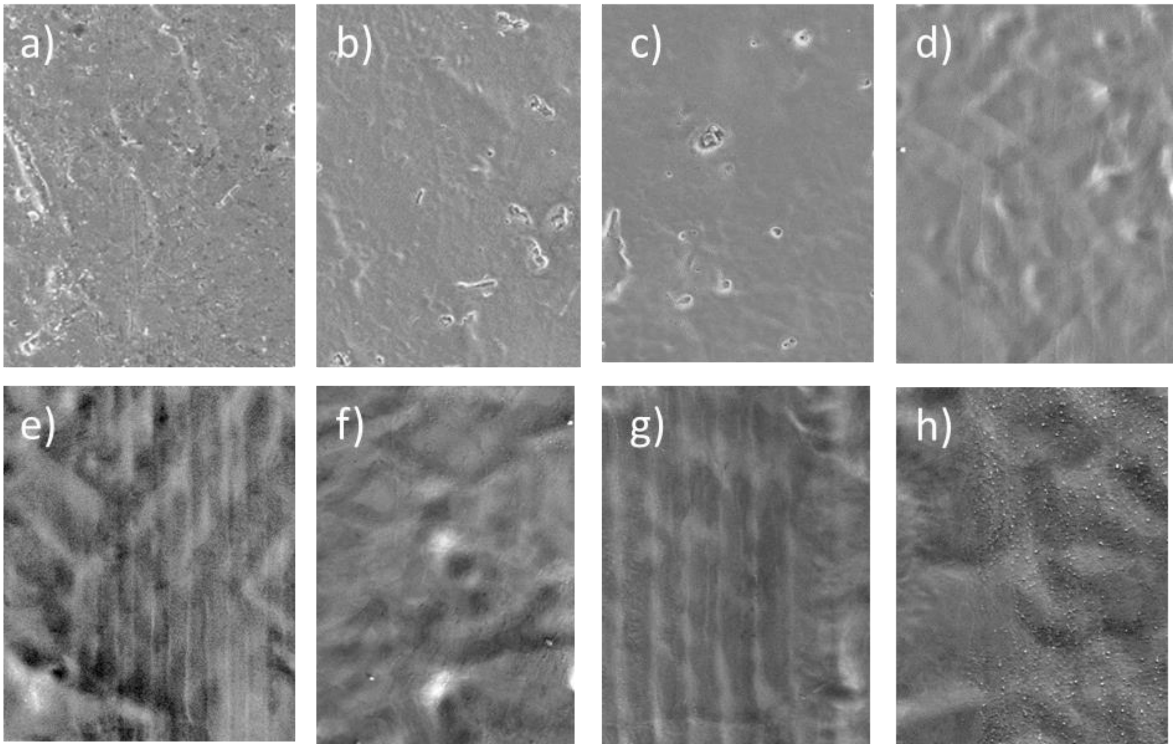

Fig. 1. SEM micrographs from samples (a) not processed ; (b) processed at 20 ns; (c) processed at 30 ns; (d) processed at 50 ns.; (e)processed at 75 ns; (f) processed at 100 ns; (g) processed at 150 ns.; (h) processed at 200 ns.

The influence of the pulse duration in the minimum affected frequency of the surface roughness (which corresponds to the maximum spatial period, i.e., the widest geometrical features affected) has been investigated. Samples have been processed at each of the pulse durations and afterwards they have been characterized in the SEM. Special interest has been dedicated to the border of the processed area, where it is possible to analyze the effect produced by the laser comparing it with the adjacent unprocessed area. In order to be able to compare the images obtained from samples processed at different pulse durations, each of them has been obtained with the same magnification of 327x. Fig 1 shows a part of the area of different samples before being processed Fig 1(a) and of samples processed at the different pulse durations Fig (b-h). The sample processed at 10 nanoseconds is not included because, due to the low output power at that pulse duration, there has not been any perceived change in the surface of the sample. On the contrary, as later will be noted, at this pulse duration a heat affected zone has been perceived.

Comparing all the images, it can be seen that as the pulse duration is increased the effect of the laser in the surface changes. In order to study more thoroughly this variation, a frequency-domain spectral analysis has been performed consisting in a two dimensional Fast Fourier Transform of the images (Fig 2). In this case, the 2D FFT has been performed without any windowing, subtracting the mean value beforehand and choosing the modulus as the output magnitude for the frequency-domain images.

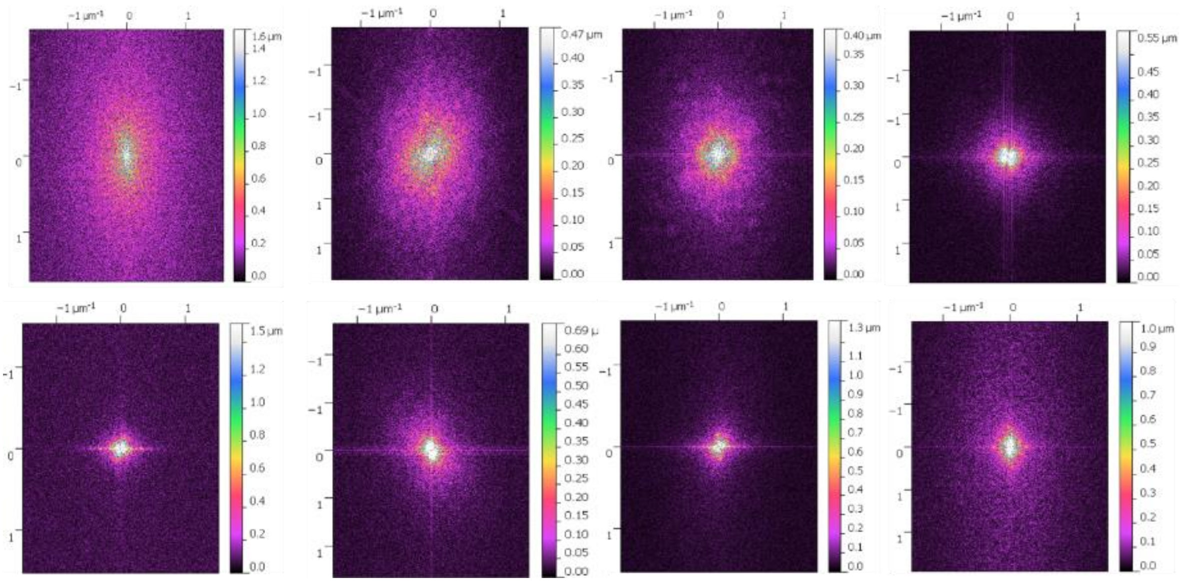

Fig. 2. 2D FFT images of the samples displayed in Fig 1 (not processed, 20, 30, 50, 75, 100, 150 and 200 ns).

As observed in the different images of Fig 2, there is a clear tendency of a narrowing of the spectra as the pulse duration increases. At 100 ns it seems that the spectrum broadens slightly comparing to 75 ns, which could be due to the irregularity of the surface of the samples. Depending on the area inspected with the SEM, the surface features that are randomly present and that are significantly bigger than the maximum affected width can affect slightly the outcome of the process.

To quantify the gradual narrowing of the spectrum, a profile has been extracted in each case and displayed in the same graph (Fig 3). In order to facilitate the analysis, and as the main aim of this analysis is to compare the relative magnitude of the different frequencies at each pulse duration, the maximum value has been normalized. The profile obtained with the sample processed at 200 ns has been excluded from the graph because, as noted in the Fig 1(h), the laser produces the apparition of spots in the surface at this pulse duration. These spots render in the SEM image as white dots that broaden the spectrum in the frequency domain Fig 2(h). To rule out the possibility of other possible origin for the spots as dust due to a not perfectly clean sample, the process has been repeated at 200 ns. The spots have also appeared in the second sample, confirming that they are a byproduct of the process.

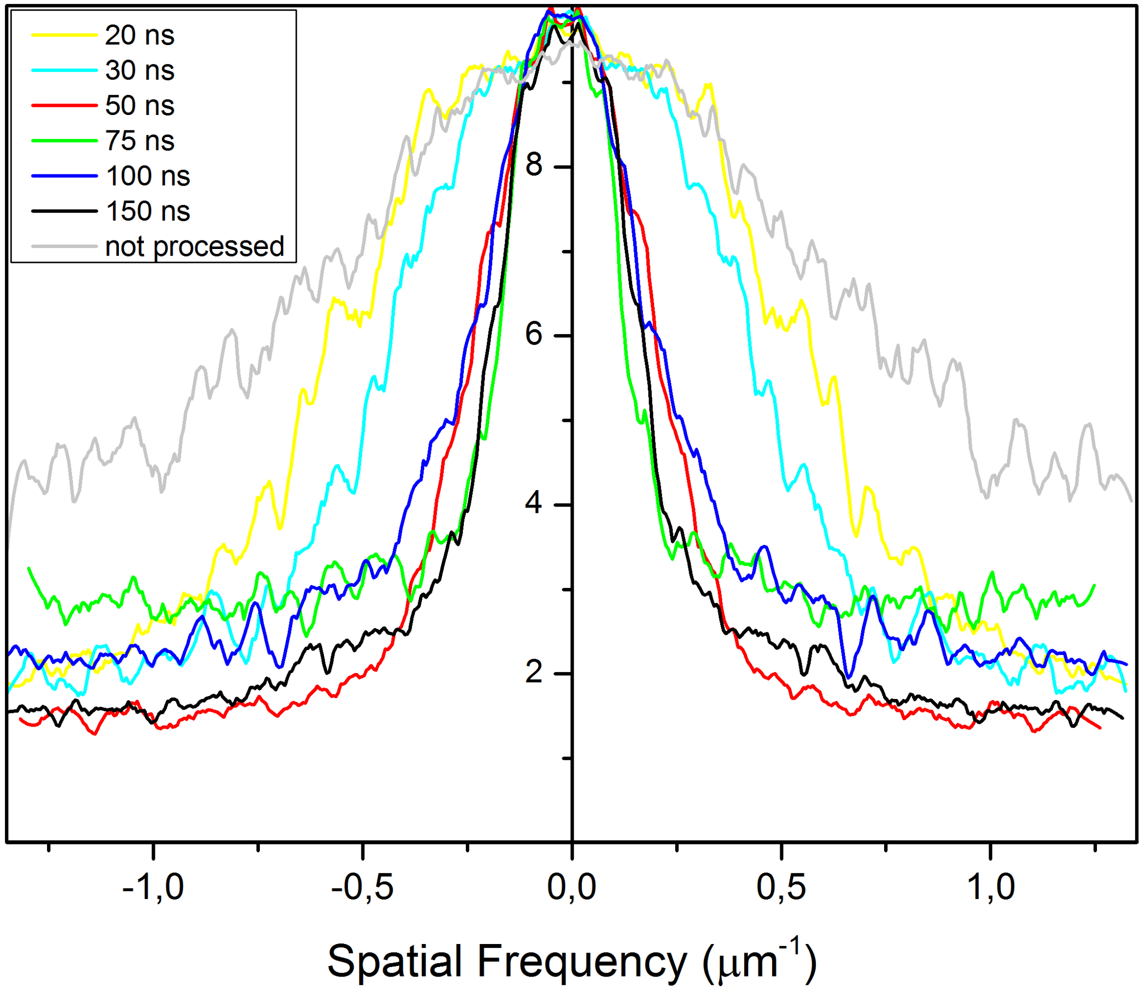

Fig. 3. Profiles extracted from the images displayed in Fig 2 except the 200 ns-processed sample.

In the Fig 3, the profiles confirm the narrowing of the spectra observed in Fig 2. Although the result at 20ns can be partially explained by the lower output power at this pulse duration, the result at 30 ns confirms that the effect of the pulse duration is the main contributor to the narrowing of the spectral profile, as the difference of the output power in this case comparing to higher pulse durations is relatively small (670 mW versus 700 mW).

A measure of the half width at half maximum (HWHM) has been performed for the profile obtained from the spectrum of the 150 ns-processed sample in order to obtain a value for the maximum affected width. As a result a spatial frequency value of 0.21 µm^{-1} has been obtained, which means that the process is able to affect surface features with a width up to 4.76 µm.

3.2. Influence of the pulse duration in the depth of heat affected zone

The second feature investigated has been the influence of the pulse duration in the depth of the heat affected zone. For this purpose, the laser treated samples have been nickel plated, cut perpendicularly to the exposed surface and methalographically polished with colloidal silica. Afterwards they have been characterized in the SEM. These results have been compared with the thermal penetration depth calculated according to equation (3) in the graph displayed in Fig 4.

The thermal affected zone (including the melted layer) is deeper than the one calculated according to Mai and Lim, 2004. The difference between the values may be due to disagreements between the theoretical and the actual values of the heat related parameters of the material, as it can be observed that the variation of both curves with the pulse duration is very similar. At the maximum pulse duration of 200 ns, the depth of the heat affected zone is of an average of 3.85 µm with a standard deviation of 0.74 µm. This means that, for applications where the heat affected zone needs to be smaller than this value, a lower pulse duration must be selected.

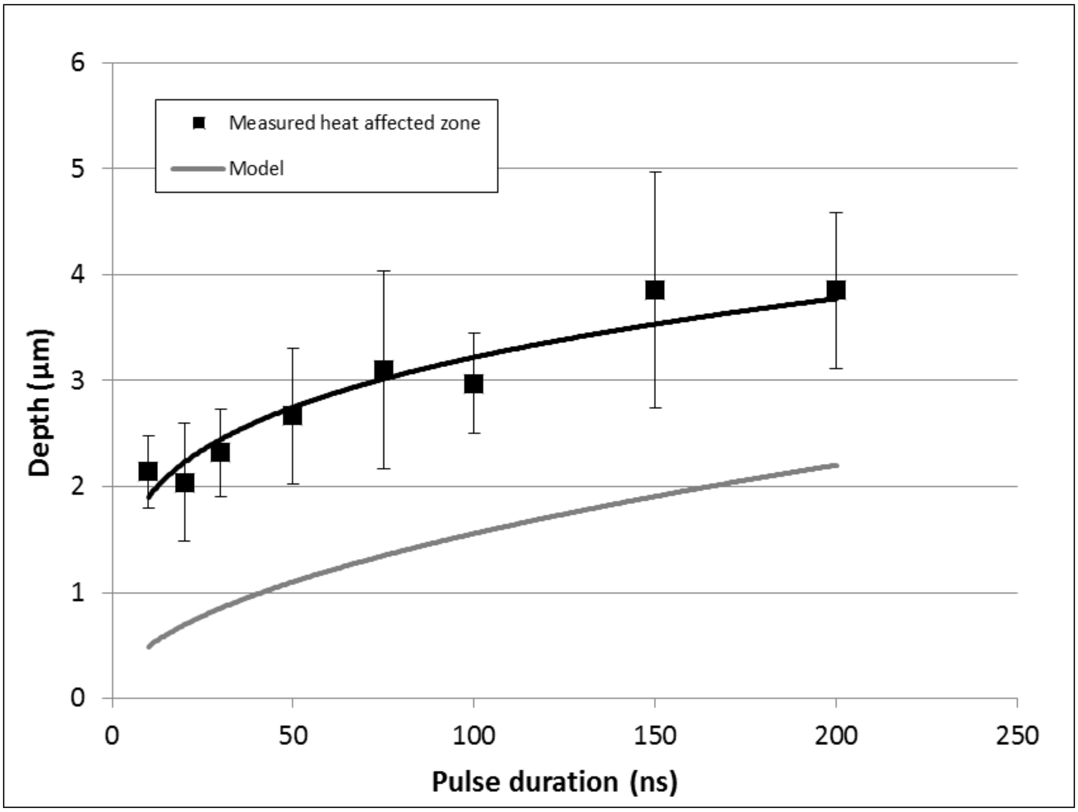

Fig. 4. Heat affected zone characterized in the SEM versus values calculated with the model.

4. Conclusions

The present work reports the effects of the pulse duration in the nanoseconds range in the laser micro polishing process. Two aspects have been analyzed: the surface roughness and the heat affected zone. In the first case the samples have been characterized using scanning electron microscopy and a posterior frequency-domain analysis of the images. A narrowing of the spectral content has been observed, which indicates an increase in the distance that can be affected as the pulse duration is increased. At 150 nanoseconds the maximum affected spatial period has been calculated at 4.76 µm (corresponding to a spatial frequency of 0.21 μm^{-1}), measuring the half width at half maximum of the profile. The sample processed at 200 ns has been discarded due to the generation of white spots related to selective material removal.

In the case of the heat affected zone, the results differ slightly from the standard model but the general trend still agrees with the predictions of the model. The maximum depth of the heat affected zone (3.85±0.74 µm) has been found, as expected, at the maximal studied pulse duration of 200 ns.

These results confirm the premise which states that, for certain applications where the structural integrity of the material is critical, a compromise must be reached between the maximum reduction of the surface roughness and the maximum heat affected depth.

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