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Laser texturing with μs pulses

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Abstract

Laser surface texturing process is based on selective material melting and vaporizing to generate a specific surface pattern. Laser surface modification has many different applications and typically short and ultra-short laser sources are used when texturing quality and almost none HAZ is required. In many applications, high quality texturing is not so critical and low-cost texturing solutions are the best option. However, ns texturing lasers are not appropiate for other applications like cutting or welding. High power CW Fiber laser sources are flexible for multiple applications and can generate μs pulses. This work was focused on the characterization and determination of optimal parameters for different surface textures using a conventional 1 kW and 5kHz laser source with μs pulses. The result show that it is possible to create several features like pin-like structures or cylindric and conic shape cavities with minimum recast material and depth to diameter ratio of 0.5.

Keywords: Laser texturing; long-pulse; engraving, dimple; pin structure

1. Introduction

Surface modification of metal parts with laser technology is an emerging application in recent years due to last laser source improvement. The target can be different depending on the needs, He et al. (2015) used laser texturing for improving the tribological properties, Hao et al. (2005) and Dunn et al.(2014) worked in reduction or increase in surface roughness, Emelyanenko et al. (2015) applied laser texturing for changing properties such as wetting angle or even like Iyengar et al. (2010) laser texturing can be used for generating a repeating surface pattern only for aesthetic purposes.

Typically, for metal surface texturing short or ultra-short laser pulses are used. Last generation pulsed laser sources allow high energy concentration or fluence, over 1mJ/cm2, in pulses of very short duration, which results in a melting and vaporizing material. This way a selective material removal is achieved. In the literature it is also common to use solid state lasers with wavelengths below 500nm [6], however, this type of source has two major drawbacks. On the one hand it is expensive equipment compared to conventional solid state laser sources of Nd:YAG, and on the other hand, have a lower resistance to industrial environment. Their design is less prepared to be integrated with other industrial equipment. Industrial laser cutting and welding sources are typically integrated in combination with robotic manipulators or Cartesian kinematic structures. Short pulse laser integration in manipulators is still something expensive and not spread in mould and die making applications.

Until now, conventional CW laser sources were rejected for texturing operations due to their limitation to work in pulse mode. This type of equipment is typically capable of operating at a frequency of between 5 and 50 kHz cycle, whereas within each cycle, the percentage of time the laser is power on can be controlled through the Duty Cycle parameter. The pulsation regime is reached by switching on and off the excitation in the resonator. This kind of sources, typically operate with pulses in the range of ms which is considered not short enough for laser texturing applications. Short and Ultra-short laser sources operate in completely different way, they use wave interference and resonator output control to reach pulses with duration in range of ps (10^{-12} seconds) and fs (10^{-15} seconds).

Usually it is considered that for metallic part texturing operation, pulse duration should be at least in the range of ns (10^{-9} seconds). However, unlike short and ultra-short lasers, the average power available in industrial lasers

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is in the range of kW. Thus, although they are limited to relatively long pulse duration, they are capable of concentrating sufficient energy to achieve a fusion and partial vaporization of material. In addition, if the settings are appropriate, is possible to work with discrete pulses and achieve selective removal of material with a minimum heat affected zone. In general, ultra-short lasers provide substantially better result with higher in precision and no thermal damage. However, in practice, there are some applications where the presence of molten material, and even a minimum thermally affected area, is perfectly acceptable.

Thus, Etsion et al. (2009) introduced applications where the final objective is the generation of dimples in the surface that act as lubricant reservoirs to maintain a constant film thickness. In the case of mechanical seals is important to ensure proper fit a constant film thickness of lubricant. These are critical elements and higher manufacturing cost derived from the use of laser technology is justified. Similarly, Vilhena et al. (2011) studied the impact of surface dimples in the friction coefficient. In the literature this surface texturing based on dimples is used on piston rings for internal combustion engines. Vilhena et al. (2011) and Kovalchenko et al. (2004) set dimple ideal dimensions between 50 and 150µm in diameter and between 5 and 20µm deep. Commonly, the texturing in these applications is carried out using short pulse lasers which has a direct impact on final part cost.

In other applications, the aim is to increase the surface roughness. Thus, there are applications for texturing friction discs of clutches used combustion engines. In Dunn et al. (2014) work the target was to improve the performance of the clutch discs by increasing roughness. In medical applications, it is also used laser texturing to improve the biocompatibility of implants by increasing surface roughness. The objective is to get a general texturing or generating grooves that facilitate tissue growth without base material contamination. For this type of operation most extended material is Ti6Al4V and several short pulse laser sources are used. Ulerich et al. (2007) instead of using more conventional Nd:YAG sources uses a Nd: YVO4 which provides better absorption rates because a wavelength below 500nm.

In this work, a study on the possibilities of an industrial 1 kW Nd:YAG fiber laser for surface texturing applications is presented. After identifying and controlling key process parameters, several experimental test were conducted in order to recreate the dimples described in the literature for applications where friction coefficient reduction is intended.

2. Expewrimental procedure

2.1. Preliminary tests

In order to determine the performance of a conventional fiber laser in texturing applications, a set of experimental tests were carried. The result was evaluated using a confocal 3D profilometer from LEICA. The tests consisted in textured areas of 15x15mm with no overlapping creating a pattern of individual features. Tests were carried out with a 1kW FL010 fiber laser from ROFIN. The output beam presents a wavelength of 1060nm and a spot size of 100µm. The output beam was guided with a galvanometric scan-head Hurry Scan 25 from SCANLAB. The workspace of the scan-head is 120x120mm and its maximum scanning speed is 10,000 mm/s. All the tests were conducted in the central area of the workspace to avoid beam scattering effects and variations in absorption due to the angle of incidence of the beam. All tests were conducted on AISI D2 tool steel that was previously hardened and surface ground to get a homogeneous part. This material is typically used in mold and die industry. Once thermal treated, the hardness is increased up to 60HRC which makes it particularly suitable for demanding applications.

The FL010 laser source is able to work in CW mode and also in pulsed mode with a frequency up to 5kHz. The beam pulses are generated by switching on and off the pumping system, so minimum pulse duration is limited by the response time of this pumping system.

The first experimental tests were carried out in order to determine the minimum pulse duration. The test consisted in several pulses with different duration and same power level. The duration in each case was adjusted to have same energy level in all cases. The power used was 1kW and frequency 5kHz. The pulse duration was modified with duty cycle percentage from 4µs to 150µs. The test duration in each case was adjusted to make constant (0.75s) the total time that laser is switched on. Table 1 shows the parameters used.

Table 1. Test for duration of the effective pulse.

Duty Cycle	Test time (s)	Pulse (µs)	Laser On (s)	Laser Off (s)
75	1.0	150	0.75	0.25
50	1.5	100	0.75	0.75
25	3.0	50	0.75	2.25
10	7.5	20	0.75	6.75
5	15.0	10	0.75	14,3
2	37.5	4	0.75	36.75

The following Figure 1 shows the resulting hole depth in each case. This depth should remain constant for all test since theoretical energy input remains constant. From the figure can be concluded that in pulses below 100µs energy output is dramatically decreased and they cannot be considered effective pulses. So, further experiments were limited to 1000µs, 550µs and 100µs.

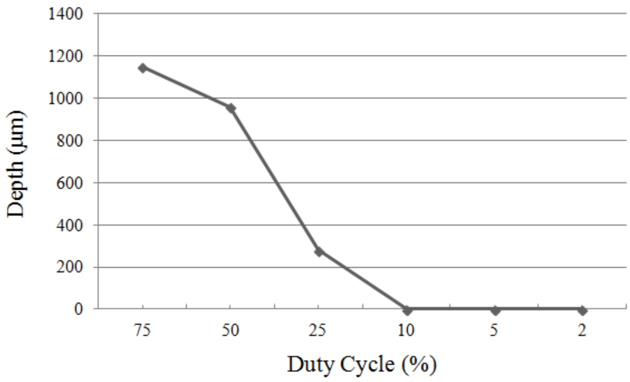


Fig. 1. Reached depth for different pulse duration.

2.2. Experimental tests

A comprehensive experimentation was carried out combining different power level for each pulse duration. In Table 2 the parameters tested are shown. In all tests the scanning speed or feed rate was adjusted depending on pulse duration so that the area on the radiation incident on each pulse remains constant at $0.011mm^2$.

Table 2. Tested parameters.

Test nº	Power (W)	Freq (Hz)	Feed rate (mm/s)	Duty Cycle (%)	Pulse Duration (µs)	Pulse Energy (kJ/cm^2)
1	200	50	30	5	1,000	1.84
2	200	91	55	5	550	1.01
3	200	1,000	300	10	100	0.18
4	250	50	30	5	1,000	2.30
5	250	91	55	5	550	1.27
6	250	1,000	300	10	100	0.23
7	300	50	30	5	1,000	2.76
8	300	91	55	5	550	1.52
9	300	1,000	300	10	100	0.28
10	350	50	30	5	1,000	3.22
11	350	91	55	5	550	1.77
12	350	1,000	300	10	100	0.32
13	400	50	30	5	1,000	3.69
14	400	91	55	5	550	2.03
15	400	1,000	300	10	100	0.37
16	450	50	30	5	1,000	4.15
17	450	91	55	5	550	2.27

18	450	1,000	300	10	100	0.41
19	500	50	30	5	1,000	4.61
20	500	91	55	5	550	2.53
21	500	1,000	300	10	100	0.46
22	550	50	30	5	1,000	5.07
23	550	91	55	5	550	2.78
24	550	1,000	300	10	100	0.51
25	600	50	30	5	1,000	5.53
26	600	91	55	5	550	3.03
27	600	1,000	300	10	100	0.55
28	1,000	50	30	5	1,000	9.21
29	1,000	91	55	5	550	5.05
30	1,000	1,000	300	10	100	0.92

The results were evaluated using a Leica DCM 3D confocal profilometer to get 3D topography, then, longitudinal and traversal profiles were extracted to evaluate the result. In each test, the resulting feature diameter was measured in longitudinal (N-S) direction and traversal (E-W) direction, being always the motion direction parallel to N-S direction. Also the maximum penetration was also measured in N-S and E-W direction, as well as the area of recast material and the resulting cavity area in both directions.

The result was very different depending on selected parameters, from holes with excessive melted material to surface marks with almost none penetration. For single pulses with fluence below 0.2kJ/cm^2 and duration of 100µs, no appreciable material removal was observed.

Regarding melted material and feature shape evolution different trends were observed depending on the pulse duration.

For 1,000µs pulses the volume of the recast material in the edge of the hole was higher in comparison with shorter pulses. During the process, when theoretical pulse fluence is below 4kJ/cm^2, material is melted and due to great thermal gradient, solidifies resulting in a ring formation in the edge of the hole (Figure 2 (a)). If pulse fluence is increased the volume of melted material becomes also higher and resolidifies even blinding the hole itself and creating a pin structure on the surface (Figure 2 (b)). Due to the relatively long duration of the pulse, the material is heated to the melting point in a larger area and because of thermal gradient and volume difference because of the new metallurgical structure, a ring of molten material is generated at the top. If pulse fluence is increased reaching values over 5.5kJ/cm^2 due to strong thermal gradient and recoil pressure the melted material is ejected and vaporized strong enough to clear the affected area and give the result shown in Figure 2 (c) and (d). In this situation there is few recast material and the feature presents big difference in top and bottom diameter.

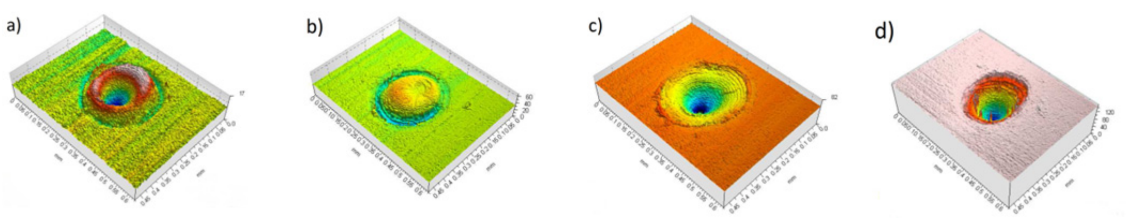


Fig. 2. 1000µs pulses with a) 3.69kJ/cm^2, b) 4.15kJ/cm^2 c) 5.53kJ/cm^2 and d) 9.21 kJ/cm^2.

Figure 2 shows the result achieved for 1000µs pulses with fluence of 3.69kJ/cm^2, 4.15kJ/cm^2, 5.53kJ/cm^2 and 9.21kJ/cm^2. In this case the pulse duration is relatively long and the material is clearly overheated. The depth of the dimple, when recasted material is present, is lower than expected being below 10µm when fluence is 3.69kJ/cm^2 and negative when 4.15kJ/cm^2. When energy is high enough, over 5.53kJ/cm^2, as it was explained, the recast material is not present and relatively wide and deep hole is reached. Extracted profile from Figure 2 (c) is shown in Figure 3.

The dimple shows conical shape with wide area on the top, 300µm in diameter, and narrow bottom, with a diameter below 50µm, while is 60µm in depth. The resulting shape shows quite smooth surface considering the process and the energy input.

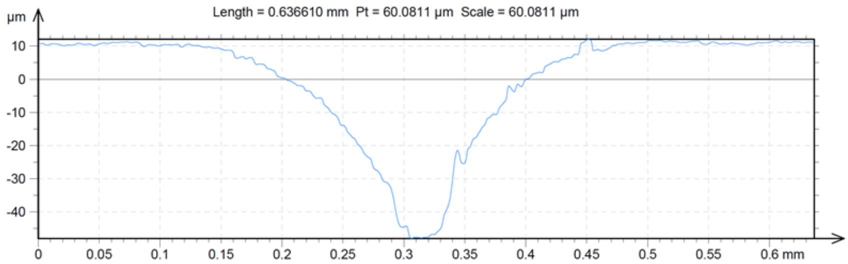


Fig. 3. Extracted profile of Test 25 with fluence of 5.53kJ/cm^2.

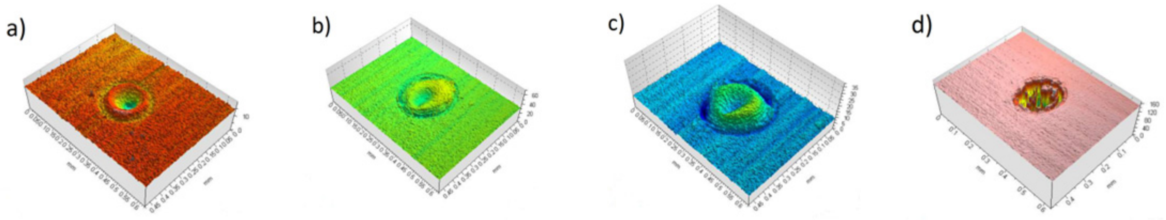


Fig. 4. 550μs pulses with (a) 1.27kJ/cm^2, (b) 2.03kJ/cm^2, (c) 3.03kJ/cm^2 and (d)5.05kJ/cm^2.

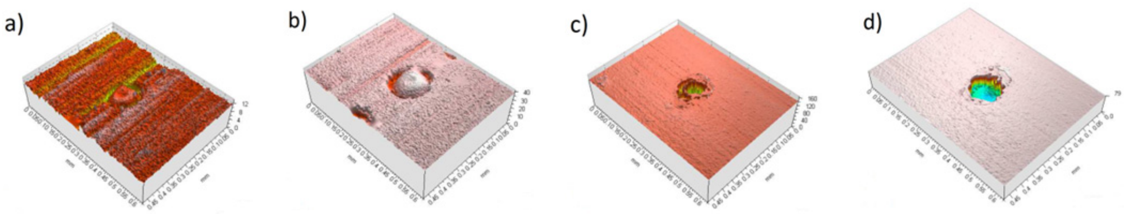


Fig. 5. 100μs pulses with (a) 0.32kJ/cm^2, (b) 0.51kJ/cm^2, (c) 0.55kJ/cm^2 and (d) 0.92kJ/cm^2.

Figure 4 and Figure 5 show the evolution of resulting geometry for 550μs and 100μs pulses with different energy density values. In the literature, Fardad (2006) sets the minimum energy density value for texturing operations is considered to be close to 0.2J/cm^2 with a maximum pulse of 20ns. In this case, since the pulse duration is significantly longer, up to 1ms, the minimum energy density necessary to remove material was significantly higher, so the result is in the limit of what is considered suitable for laser texturing.

When optimal parameters are set, the regimen obtained was satisfactory with goof result for texturing applications where the goal is to create dimples to improve lubrication. Thus, for a power of 1,000W, with a cycle frequency of 1kHz. a duty cycle of 10% and a scanning feed rate of 300mm/s (Test 30 in Table1) the result is close to the target geometry described in the introduction. Figure 6 shows the result achieved in this case.

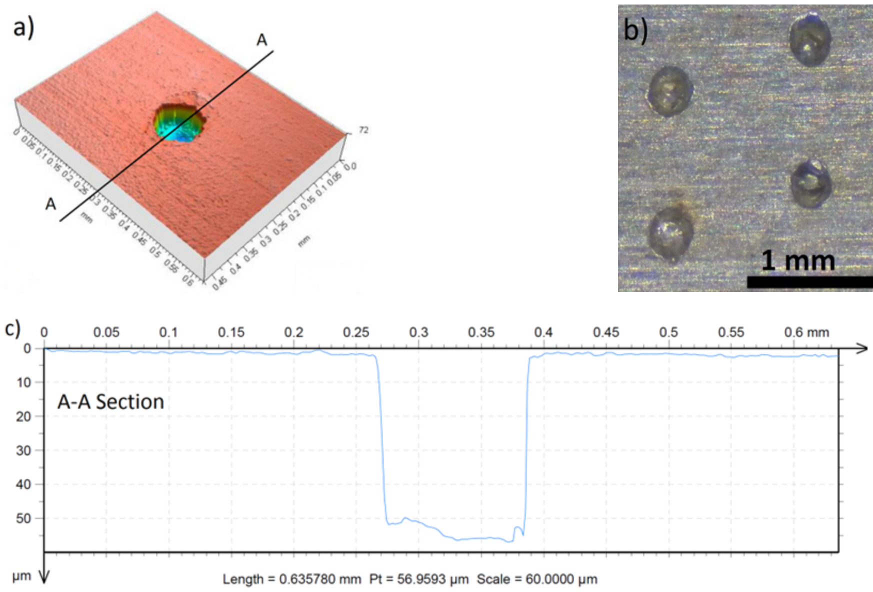


Fig. 6. (a) 3D measurent; (b) dimples and (c) extracted profile

In this case, with a pulse of 100µs and energy density of 0.55kJ/cm^2 the final dimple geometry is close to one described in the literature as optimum. Thus, the reached geometry is about 100µm in diameter and 50µm deep. Furthermore, the amount of material solidified in top surface is almost noticeable and no undermelted areas within the cavity can be appreciated. Although initially was expected some negative effect due to non-uniform energy distribution in the spot since solid state multimode laser beam was used. Nevertheless there is no evidence of any significant irregularity. In comparison with previous result described in Figure 4, the parameters provide better result. This point suggests some relation between cycle frequency and energy distribution within the beam spot that must be studied in further work.

3. Results and discussion

With a conventional fiber laser working in pulsed mode is possible to reach some interesting laser textured geometries. Tests carried out shows that it is possible to create holes with surrounding recast material, pin-like geometries and holes with almost no recast material on the top surface.

In order to evaluate the result the resulting geometry width was measured in N-S and E-W direction. Also, to depth of the cavity or height of the resulting pin was measured from initial reference plane. Figure 7 shows the result achieved when energy density is increased for pulse duration of 1,000µs, 550µs and 100µs.

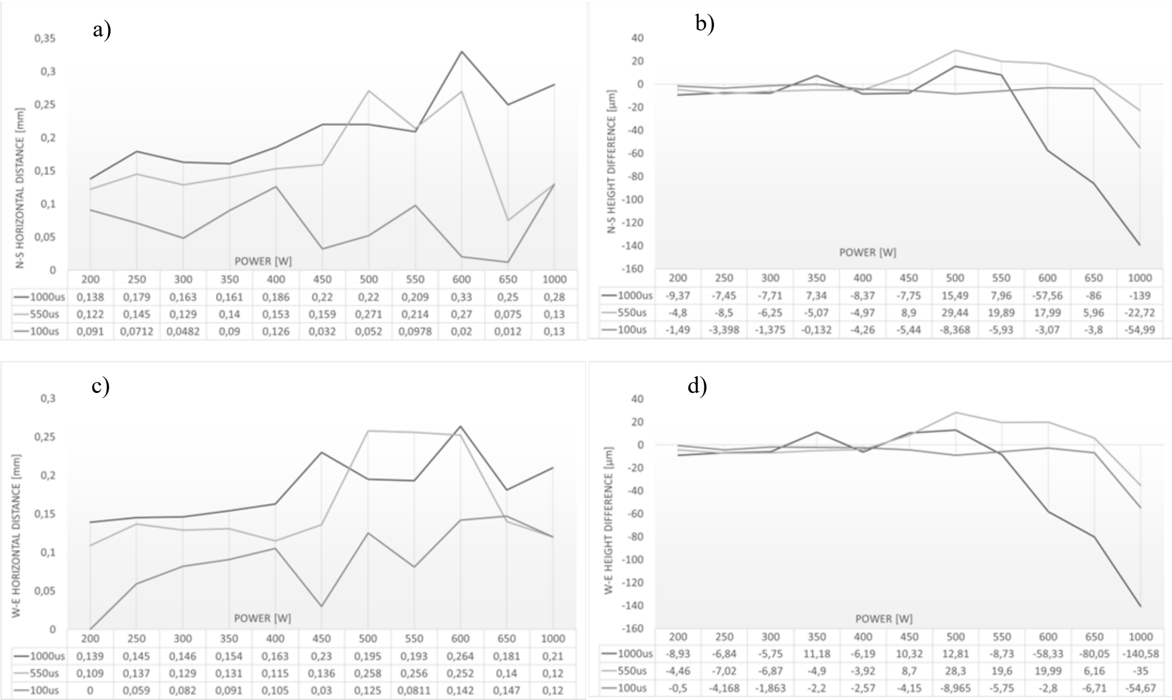


Fig. 7. (a) Dimple diameter and (b) depth in N-S direction and (c) diameter and (d)depth in W-E direction.

Figure 7 (a) and (c) shows that larger diameter is reached for longer pulse duration. The theoretical beam diameter is about 100µm and depending on beam power and pulse duration the reached feature diameter is between 50µm and 250µm. In Figure 7 (b) and (d) it can be appreciated that when beam power is increased, for longer pulses the resulting feature changes from pin-like shape to a cavity. A fluence over 5kJ/cm^2 and pulse duration of 1000µs generates ablation plume and melted material is ejected with no recast. Once reached this situation higher power generates deeper and wider cavities (Figure 2 (d)). With most energetic parameters a cavity of 250µm in diameter and 160µm in deep was achieved. For 100µs pulses the diameter of the resulting surface feature remains below 100µm when fluence is below 0.5kJ/cm^2. With fluence between 0.5 and 1kJ/cm^2, the material is also removed with less heat affected area and lower penetration, reaching a cavity about 100µm in diameter and 50µm deep.

With 550µs pulses it is also appreciated a transition from pin-like features to cavity formation. The maximum height of pins is also 20µm, similar to ones reached with 1000µs and the cavity shows some under-melted structures because of lack of melting (Figure 4).

Another way to evaluate the result is the evaluation of melted and ejected material proportion. Using a tool of LEICAMAP software to evaluate the extracted profile, the proportion in area of recast material in the surface and the area of the cavity was measured, like it is shown in Figure 8. Results are shown in Figure 9 and similar behavior is appreciated in both N-S and E-W directions. In this case, Figure 9 (a) and (c) shows that the hole area is clearly increased when threshold energy value is reached. This threshold energy level also depends on pulse duration, thus for 1,000µs pulses is about 5.07kJ/cm^2 while for 100µs this value is close to 0.55kJ/cm^2. This increase in dimple depth is also coherent with a reduction of recast material, Figure 9 (b) and (d).

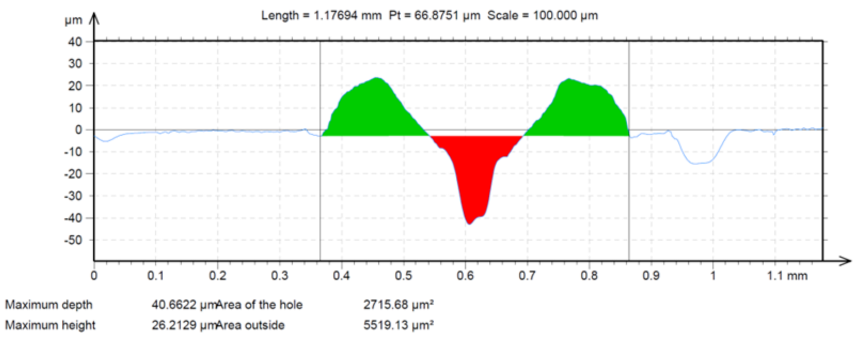
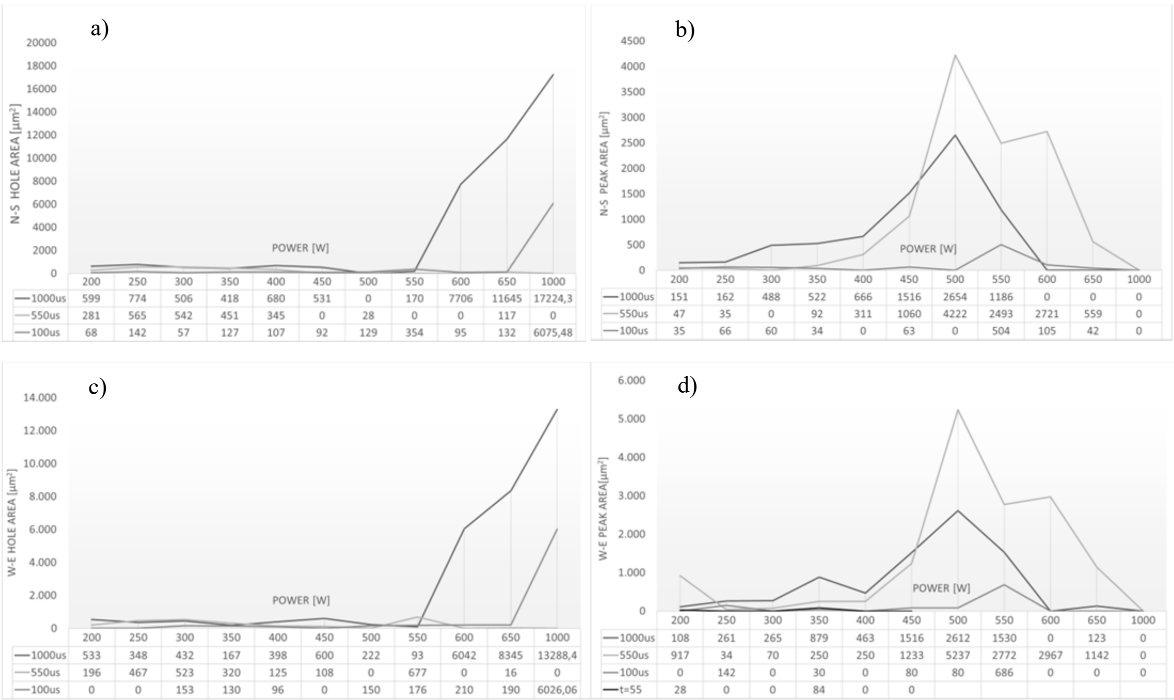


Fig. 8. 1000µs **p**ulses with 3.69kJ/cm² (a) 4.15kJ/cm² (b) and 5.53kJ/cm².



a)

	200	250	300	350	400	450	500	550	600	650	1000
1000us	599	774	506	418	680	531	0	170	7706	11645	17224,3
550us	281	565	542	451	345	0	28	0	0	117	0
100us	68	142	57	127	107	92	129	354	95	132	6075,48

b)

	200	250	300	350	400	450	500	550	600	650	1000
1000us	151	162	488	522	666	1516	2654	1186	0	0	0
550us	47	35	0	92	311	1060	4222	2493	2721	559	0
100us	35	66	60	34	0	63	0	504	105	42	0

c)

	200	250	300	350	400	450	500	550	600	650	1000
1000us	533	348	432	167	398	600	222	93	6042	8345	13288,4
550us	196	467	523	320	125	108	0	677	0	16	0
100us	0	0	153	130	96	0	150	176	210	190	6026,06

d)

	200	250	300	350	400	450	500	550	600	650	1000
1000us	108	261	265	879	463	1516	2612	1530	0	123	0
550us	917	34	70	250	250	1233	5237	2772	2967	1142	0
100us	0	142	0	30	0	80	80	686	0	0	0
t=55	28	0	0	84	0	0					

Fig. 9. (a) hole area and (b) recast area in N-S direction and (c) hole area and (d) recast area in W-E direction.

From experimental tests carried out can be stated that a conventional fiber laser is suitable for some laser texturing applications. Tests carried out shows that there are two relevant parameters to be considered. On one hand the energy density or fluence and pulse duration on the other. An energy density close to 0.25kJ/cm^2 was high enough for the selective removal of material and to get a suitable geometry. Moreover, the pulse duration has direct impact on material melted volume during the process. In the tests, pulses longer than 600μs cause an excess of melted and resolidified material volume. In a conventional laser, where the pulse duration and amount of energy emitted in each pulse is limited by the excitation mechanism, a balance must be found. Thus for a 1kW Nd:YAG fiber laser with a maximum cycle frequency of 5 kHz the optimal parameter combination found was for 100μs pulse with an energy density of 0.55kJ/cm^2..

Another relevant factor that significantly affects the quality of textured surface is the multi-mode or single mode configuration of the laser source. Thus, single mode source presents a Gaussian energy distribution within the spot, however, multimode source presents a combined energy distribution, where each mode provides a different energy distribution [Fardad 2006]. The addition of all these modes provides a Top-Hat energy distribution, which theoretically is more uniform than a Gaussian distribution. However, the tests carried out, in overlapped engraving, showed that the effect of a multimode distribution may affect the result significantly if the parameters are not optimized. Thus, in Figure 5 the resulting cavity shows some non-melted areas due to this effect. This problem can be minimized in two ways. First of all with an optimized hatching strategy, and secondly, with an additional processing of the area in laser polishing regime. Laser polishing is a process based on the selective melting of a thin layer and can reduce the resulting surface roughness up to 80%[Ukar et al. (2010)]. A productivity rate of 1 cm^2/min was achieved in engraving test. This productivity rate is in the range of other conventional laser texturing applications [Toyserkani et al. (2015)], but can be improved working with higher spot diameter and optimizing the hatching strategy.

In long pulses, in the range of 1ms, if the fluence is over 3kJ/cm^2 there is an excess of melted material that solidifies resulting in a ring shape feature surrounding the beam area of incidence. In some cases, like Test 16 in Table1, the melted material blinds completely the hole and creates a pin-like feature significantly higher than reference surface. This fact suggests a difference between the melted and solidified material volume. This can be explained because of the metallurgical and grain size changes after solidifying. Another point to consider is the creation of a depression next to the ring described. This fact can be appreciated in Figure 2 (a) and (b) and can be explained because of the relatively large amount of material melted and the high thermal gradient that generates convection currents and material displacement within the generated melt pool [Ukar et al. 2010]. Nevertheless the thermal effect of the material and dimensions of the heat affected zone (HAZ) should be evaluated.

4. Conclusion

Conventional Fibre laser of 1kW with CW and up to 5kHz pulse working mode was used for texturing applications. The resulting dimples geometry present a regular shape with 100µm in diameter and 50µm depth which is almost the optimal shape described in the literature for friction reduction applications. The pulse energy and pulse duration are the key parameters in the process. In conventional lasers, pulses longer than 1ms generate an over-melt area and large heat affected zone, with re-solidified material in the surface. The best results were obtained for 100µs pulses with 0.55kJ/cm2 energy density. The tests showed that the final result is limited by the low energy density at pulses below 100µs and the irregular energy distribution on the spot if the laser source configuration is multimode. Results show that it is possible to remove material selectively using a long pulse laser source, in engraving tests an irregular topography was obtained in the bottom of the laser processed area requiring another operation in laser polishing regime. Despite the results were successful, due to the high energy processing conditions it is necessary to carry out a thermal study to evaluate the HAZ and the metallurgical structure near the areas processed.

In some conditions, despite they are far from the initial target geometry, some interesting features were obtained. With long pulses (1ms) and high fluencies, between 4.15 and 5.53kJ/cm^2 is possible to create pin like structures on the surface and quite deep holes with wide top diameter and narrow bottom diameter. These features are potentially interesting for applications like dissimilar material joints and its formation mechanism should be more in deep studied. In the tests, pulses longer than 500µs cause an excess of melted and resolidified material volume. In a conventional laser, where the pulse duration and amount of energy emitted in each pulse is limited by the excitation mechanism, a balance must be found. Thus for a 1kW Nd:YAG fiber laser with a maximum cycle frequency of 5 kHz the optimal parameter combination found was for 100µs pulse with an energy density of 0.55kJ/cm^2.

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