

LiM 2011

Analysis of the Influence of Burst-Mode Laser Ablation by Modern Quality Tools

Claus Emmelmann, Juan Pablo Calderón Urbina *

*Institute of Laser and System Technologies (iLAS),
Hamburg University of Technology (TUHH), Denickestraße 17, 21073, Hamburg, Germany*

Abstract

The development of lasers in terms of pulse length and ablation quality has made wider the perspective of material processing. Ablation using picosecond lasers offers an almost “cold material removal”, which causes minimal heat affected zones and enables sublimation without melt formation. Moreover, burst-mode intensifies these effects by the partition of pulses into groups of micro-pulses. Therefore, removal rate and surface quality are improved with an appropriate combination of burst-mode and other relevant process parameters. Nevertheless, parameter identification can be costly and time demanding. Thus, analysis of parameter impact offered by modern quality tools represents a convenient approach to accelerate ablation process improvements.

Keywords: burst; laser ablation; picosecond laser; quality; Shainin

1. Introduction

Laser material processing has shown its capabilities in several industrial activities in areas of macro and also micro applications. Some examples of micro applications using pulsed lasers are the ablation of ultra hard materials and synthetic diamonds, structuring of metals, ceramics and plastics, as well as drilling of titanium and compound materials, among others. Moreover, the quality results of the laser ablation process can be as good as traditional industrial machining processes (e.g., roughness), and in some cases even better, as in micro-drilling. The evolution of pulse length has also contributed to the expansion of applications by offering ultra-short pulses from nano (ns) to femtosecond (fs) durations [1]. Therefore, the interaction of picosecond (ps) and femtosecond laser pulses with material releases the possibility of an almost “cold ablation” where the time of energy absorption is short enough to remove material and avoid side-effects like burns, plasma formation, crack origination and rough surfaces [2]. This advantage permits its use for applications that seek polished surface quality and higher ablation rates.

In the past years, the concept of burst mode has been developed by laser source manufacturers; nevertheless, its physical relationship and impact on different materials is only partially known. The first approaches to the application of burst-mode laser ablation have shown relevant outcome, mainly in material removal rates. In addition,

* Corresponding author. Tel.: +49-40-42878-4465; Fax: +49-40-42878-4076.
E-mail address: juan.calderon@tuhh.de.

preliminary research has released interesting conclusions in surface machining. However, extensive research with some materials could become costly and time consuming. This threatens its economic feasibility and as a consequence, its final industrial application. Titanium or polycrystalline diamonds are some examples of those materials that have high cost and where economical experimental activities have to be considered [3, 4, and 5].

This investigation reports the results of laser ablation using a ps laser with the feature of burst-mode. The aim of this paper is to present an approach for the identification of the relevance of burst-mode among selected variables of laser ablation in terms of roughness and ablation rate. Based on the Shainin methodology, the influence of the parameters can be quantified and used to isolate parameters of high significance [6]. This eliminates the use of costly and time consuming full-factorial experiments with many parameters applied to new or non-extensively researched materials.

2. Burst-mode laser ablation

In areas of micro processing, laser ablation has become a useful alternative to traditional technologies, e.g., milling, grinding and electrical discharge machining among others. In definition the laser ablation process separates material (solid, liquid or vapor) from a solid by means of optical energy induced processes initiated by laser beam exposure [7]. Moreover, laser ablation has become a characteristic process for pulsed lasers because of its short thermal interaction with the processed material.

Solid-state ps lasers being used under this experimentation, reduce the interaction of laser and material within a pulse duration (τ) of 8 to 12 ps and avoid melt formation by terms of minimal thermal side-effects and sublimation [2, 8]. The used laser source of the company Lumera performs a high beam quality TEM_{00} $M^2 < 1.5$, three wavelengths (λ) 1064 nm, 532 nm and 355 nm and an average power of 50 W at 1064 nm for instance. Repetition rates (ν) 400 kHz, 500 kHz, 800kHz and 1000 kHz are applicable emitting a pulse energy of 125 μ J, 100 μ J, 63 μ J and 50 μ J (under 1064 nm), respectively [9].

The laser beam releases pulses of ps length up to 1000 kHz. These pulses can be partitioned up to ten times in micro pulses or bursts. As a consequence, the pulse energy is split into the determined number of bursts. In other words, the burst-mode is the partition of laser pulses into smaller pulses. These pulses come together in a group, followed by a pause (nanosecond interval) before the next group of bursts is released. According to the manufacturer, the burst-mode technology platform is composed of an oscillator (< 10 ps) that creates a beam at approximately 50 MHz. This pulsed beam crosses a switch to the transient amplifier, whose aperture remains open longer and which yields laser bursts with 20 ns separation Δt (see Figure 1) [5].

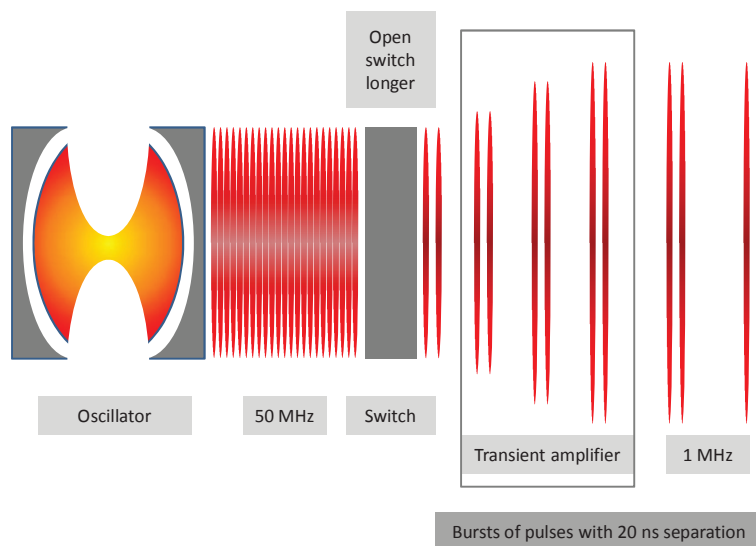


Figure 1: Burst-mode technology platform [5]

For this analysis with Shainin variable search, bursts of 8 pulses were used under 400 kHz and 800 kHz (as schematized in Figure 2). Within the bursts, there is an interpulse separation of $\Delta t = 20$ ns. The contrast level in this parameter was single pulse (without burst-mode). The selected parameters and their levels for this study will be explained in detail in the experimental set-up. The pulse energy using 50 W for 400 kHz and 800 kHz is 125 μ J and 63 μ J, respectively. Therefore, the burst energy using burst-mode in this study equals to 125 μ J divided by 8 bursts at 400 kHz and 63 μ J divided as well by 8 bursts at 800 kHz.

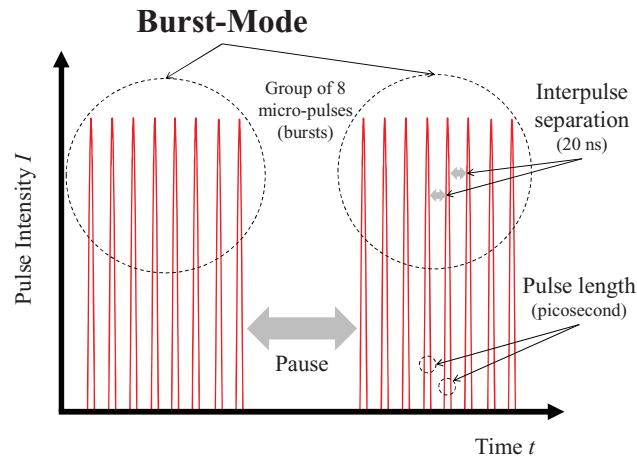


Figure 2: Schematic representation of burst-mode with 8 bursts

3. Analysis of the influence of burst-mode laser ablation by modern quality tools

The first step in the analysis of the influence of burst-mode laser ablation is the determination of the related parameters. This has to be done in a top down approach to include all possible variables that are related to the process and its objectives. The Ishikawa diagram offers a clear target oriented arrangement of the variables where interactions can be schematically understood [6, 10, and 11]. Figure 3 illustrates the Ishikawa diagram for laser ablation, where the objectives are minimization of roughness and maximization of ablation rate.

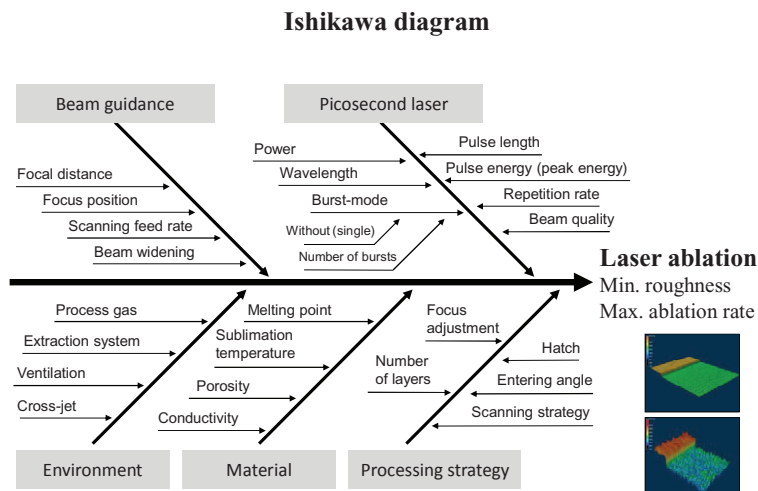


Figure 3: Ishikawa diagram for the analysis of the influence of burst-mode laser ablation

The illustration comprises several variables that have an influence on the quality targets. Some of them are not controllable due to procedural or physical circumstances, e.g., the material and its properties. On the other hand, there are variables that are controllable and have direct effect on the objective. Hence, a broad perspective can be gained and the system behavior can be delimited onto the input – output relationship. For this research, laser power, repetition rate, burst-mode, focus position, scanner feed rate and hatch distance have been selected.

Shainin Method

Component search or variable search is a technique that leads to the quantification of the impact of relevant parameters in a process based on the 20/80 Pareto concept. From a large number of influencing factors, it is possible to reduce the factors to a manageable and controllable number by identifying the variables with the biggest influence. As a result of the method, there are only few variables that are necessary for extensive investigation. “Red X” variables are named the factors that have a strong impact on the output (objectives). Additionally, there are as well variables that present an impact to the output but in a lower degree than the “Red X”, these are called “Pink X” [6].

The method consists of three main stages: choice of parameters and their respective levels, preliminary experimentation, and main experimentation or elimination stage. It can be added a phase where validation of the experimentation is achieved [11, 12 and 13]. The first stage, choice of parameters and levels, has to include the variables that can be controlled directly. Then, the levels have to be set attempting to achieve a good qualitative setting and a bad qualitative setting. The first is likely to produce good results, and the second is likely to produce poor results, respectively. For this investigation the parameters are set for the minimization of roughness R_a (surface quality). Secondly, the preliminary experiments are executed. These yield reference values for comparison. The results of the preliminary experiments also have to fulfill the statistical test ($D/d \geq 5/1$) based on the classical F table [6, 12]. Finally, the main experimentation is carried out by running a test with each parameter in a good qualitative level and the rest of the factors in a negative qualitative level, and vice versa. At the end, the variables that resulted with the greatest influence are arranged in a validation experiment, where these are set to a good qualitative level and the rest in a negative qualitative level, and vice versa.

In the next section, the application of the Shainin method for the analysis of the influence burst-mode laser ablation will be discussed in detail.

4. Experimental set-up

4.1. Material choice and equipment

The experiments of this study were carried out on laser generated plates made of tool steel 1.2709 (steel according to ISO norm). The dimensions of the plates are 20 x 40 x 5 mm ($L \times W \times H$). Besides being a common material for laser additive manufacturing (LAM), laser generated tool steel offers also further finishing opportunities for laser ablation. LAM is a process where thin layers of powder are laid on a building platform and molten due to the thermal influence of a laser exposure [14]. Parts being generated by LAM show bad roughness, and as a consequence, a high finishing improvement potential. The samples for this study perform a roughness of R_a value of 13 to 20 μm .

Laser material ablation was achieved using a 50 W ps laser (Lumera Hyper 50) emitting in infrared wavelength ($\lambda = 1064 \text{ nm}$). Beam guidance was realized by a commercial mirror scanner (hurryScan Scanlab) working with typical marking speed of 3.5 m/s and positioning speed of 15 m/s.

For the measurement of the quality attributes, i.e., roughness (R_a) and dimensions for ablation rate a confocal laser scanning microscope was used (Keyence, VK 8710 Color 3D laser scanning microscope).

4.2. Experimental procedure

A square cavity shape with edge length of 5 mm was selected for the ablation executed on the tool steel plate for the application of the Shainin method.

An important point to take into consideration is the interaction of laser power, scanner feed rate and hatch distance. The different combinations of its levels ablate differently. This is because of the number of pulses and pulse trajectories that expose the material, e.g., a large hatch distance and a fast scanning speed will obtain less ablation compared to a narrow hatch distance and a slow scanning speed. Therefore, the depth was kept constant by adjusting the number of layers of laser exposure. For this study, the depth was kept at 3 mm.

As mentioned above, the objectives of this investigation are minimization of roughness (R_a) and maximization of ablation rate (calculated from ablation depth, square dimensions and processing time). For this reason, the objective of the Shainin method in this study is to identify the parameters that represent the greatest influence to these targets. An important point to remark is that ablation rate and roughness manifest a contrary effect, i.e., the increase of ablation rate reduces the surface quality and the improvement of surface quality reduces the ablation rate.

The reference values in the Shainin method will work as qualitative borders to identify the direction of the influence (if exists) of the parameters.

Once the objectives have been set, the first stage in the variable search of Shainin is the choice of the parameters and its setting. Table 1 lists the selected parameter and its respective qualitative positive or negative setting (Best Q^+ or Worst Q^- , respectively). In other words, the column Best Q^+ is aimed to achieve the qualitative best results and Worst Q^- is aimed to obtain the qualitative worst results.

Tab.1. Choice of parameters

Factors	Settings	
	Best Q^+	Worst Q^-
A Laser power [W]	12.5	25
B Repetition rate [kHz]	800	400
C Burst-mode [Number of bursts]	8	1*
D Focus position [from surface mm]	0	-1
E Scanner feed rate [mm/s]	5000	1000
F Hatch [mm]	0.006	0.03

* Single pulse (without burst)

Once parameters and settings were selected, the second stage of the method is executed, i.e., preliminary experimentation. Table 2 presents the results of the Best Q^+ and Worse Q^- runs for the ablation rate and table 3 for the roughness (R_a). To accomplish the statistical test ($D/d \geq 5/1$) based on the classical F table [6, 12], two runs of each experiment are needed. The average result of both experiments becomes the reference value for the main experimentation. It is important to remark that the best and worst values are qualitatively oriented. This is especially important for the understanding of good and bad values with the ablation rate.

Tab.2. Preliminary experimentation for ablation rate

Experiments	Results ($\text{mm}^3/\text{s} \times 10^{-6}$)	
	Best Q^+	Worst Q^-
1 st Preliminary experiment	6	33
2 nd Preliminary experiment	5	32
Reference value (V)	5.5	32.5

Tab.3. Preliminary experimentation on surface roughness

Experiments	Results R_a (μm)	
	Best $Q+$	Worst $Q-$
1 st Preliminary experiment	4.19	30.87
2 nd Preliminary experiment	6.38	32.65
Reference value (V)	5.29	31.76

The result on the first preliminary experiment of each objective can be observed in Figure 4. The depth of the ablation can be identified in the topographic laser confocal microscope images in Figure 4a and 4c. Figure 4b and 4d visualize the difference in roughness.

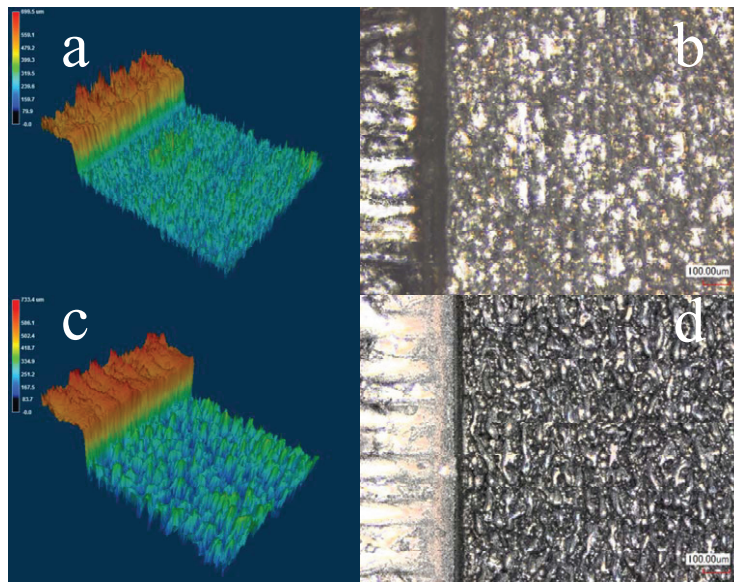


Figure 4: 1st preliminary experiment for ablation rate, topographic image (a) and above (b), 2nd preliminary experiment on surface roughness, topographic image (c) and above (d)

Once the reference values for each objective are known, the main experiments are launched (third stage of Shainin method). For the first run, laser power is set to its qualitative negative level (25 W) and the rest of the factors are set to their qualitative positive level. The second run presents the inverse setting, i.e., laser power is set to its qualitative positive level (12.5 W) and the rest of the factors are set to their qualitative negative level. Subsequent runs follow the same described methodology with the variables executed one at a time. Lastly, these experiments release important contrast information that can denote the influence variables.

The experimental combinations and their respective results of the main experimentation are given in table 4. Next to the result of each combination, the corresponding reference value (V+ or V-) can be observed. A similar result to the corresponding reference value would hint at a little influence in the objective. On the other hand, a greater difference would insinuate a positive or negative influence depending on the influence direction.

Tab. 4: Results of the main experimentation for ablation rate (left) and roughness (right)

Main experimentation Ablation rate [mm ³ /s x 10 ⁻⁶]					Main experimentation Roughness R _a [μm]				
Factors	Combination	Results	V ₊	V ₋	Factors	Combination	Results	V ₊	V ₋
		[mm ³ /s x 10 ⁻⁶]	[mm ³ /s x 10 ⁻⁶]	[mm ³ /s x 10 ⁻⁶]			[μm]	[μm]	[μm]
A Laser power	A.R ₊	27	5.5		A Laser power	A.R ₊	1.43	5.29	
	A.R ₋	18		32.5		A.R ₋	12.19		31.76
B Repetition rate	B.R ₊	10	5.5		B Repetition rate	B.R ₊	7.48	5.29	
	B.R ₋	35		32.5		B.R ₋	34.28		31.76
C Burst-mode	C.R ₊	14	5.5		C Burst-mode	C.R ₊	3.76	5.29	
	C.R ₋	80		32.5		C.R ₋	16.28		31.76
D Focus position (from surface)	D.R ₊	2	5.5		D Focus position (from surface)	D.R ₊	9.27	5.29	
	D.R ₋	39		32.5		D.R ₋	24.80		31.76
E Scanner feed rate	E.R ₊	5	5.5		E Scanner feed rate	E.R ₊	4.18	5.29	
	E.R ₋	17		32.5		E.R ₋	14.48		31.76
F Hatch	F.R ₊	2	5.5		F Hatch	F.R ₊	10.31	5.29	
	F.R ₋	34		32.5		F.R ₋	24.87		31.76

5. Experimental results and discussion

Once the main experimentation and its evaluation is complete, significant information for the analysis of the influence of burst-mode and other parameters of laser ablation is available.

Figure 5 depicts the behavior of the different experimental runs and their reference values for ablation rates. It is clearly noticeable that factor C, burst-mode, provides a significant influence to the objective. In others words, the qualitative positive setting of burst-mode (8 bursts) presents a relevant contrast when the rest of the factors is set qualitatively negative. Furthermore, factor A (laser power) presents a strong reversal of its results, i.e., 25 W (qualitative negative setting) shows higher ablation rate than 12.5 W (qualitative positive setting).

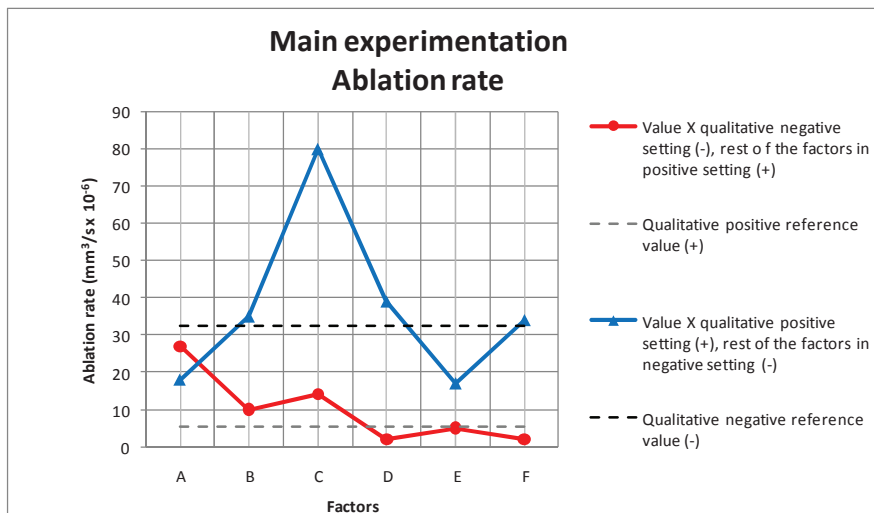


Figure 5: Ablation rate results of the Shainin main experimentation

In addition, there are two parameters that present a minor influence to ablation rate. These can be named after Shainin “Pink X” [12]. Repetition rate (factor B), focus position and scanner feed rate can be considered “Pink X”.

However, scanner feed rate is a factor that does not positively influence the ablation rate, but it decreases the rate in both settings. The behavior change compared to the reference value is quantified (percentage) in table 5.

Tab. 5: Ablation rate results of the Shainin main experimentation

Main experimentation Ablation rate [mm ³ /s x 10 ⁻⁶]					Analysis		
Factors	Combination	Results	V ₊	V ₋	%	Variation average (%)	Conclusion
		[mm ³ /s x 10 ⁻⁶]	[mm ³ /s x 10 ⁻⁶]	[mm ³ /s x 10 ⁻⁶]			
A Laser power	AR ₊	27	5.5		391	173	1° Red X
	A ₊ R ₋	18		32.5	-45		
B Repetition rate	BR ₊	10	5.5		82	45	3° Pink X
	B ₊ R ₋	35		32.5	8		
C Burst-mode	CR ₊	14	5.5		155	150	2° Red X
	C ₊ R ₋	80		32.5	146		
D Focus position (from surface)	DR ₊	2	5.5		-64	-22	less relevant
	D ₊ R ₋	39		32.5	20		
E Scanner feed rate	ER ₊	5	5.5		-9	-28	less relevant
	E ₊ R ₋	17		32.5	-48		
F Hatch	FR ₊	2	5.5		-64	-30	less relevant
	F ₊ R ₋	34		32.5	5		

In short, the “Red X’s” in the experimentation pursuing ablation rate are laser power and burst-mode. Additionally, repetition rate is considered as “Pink X”.

Regarding the roughness, Figure 6 shows the behavior of the factors in the main experimentation. Again, as seen in terms of ablation rate, laser power (factor A) and burst-mode (factor C) offer a strong influence to the objective. It can be observed that laser power influences the roughness in both directions. Subject of further research will be the interaction of laser power with other factors. Moreover, burst-mode shows high influence to the roughness quality of the LAM samples. Furthermore, burst-mode might also be subject of interaction with other factors. Even when there is a great influence, there is not a marked improvement of the roughness. As a matter of fact, there is a decrease in surface quality (number of bursts is subject of detailed analysis). It is important to reconsider this point for further research. The factors with the greatest influence on the roughness (“Red X”) are laser power and burst-mode. Scanner feed rate resulted as a “Pink X” factor (see table 6).

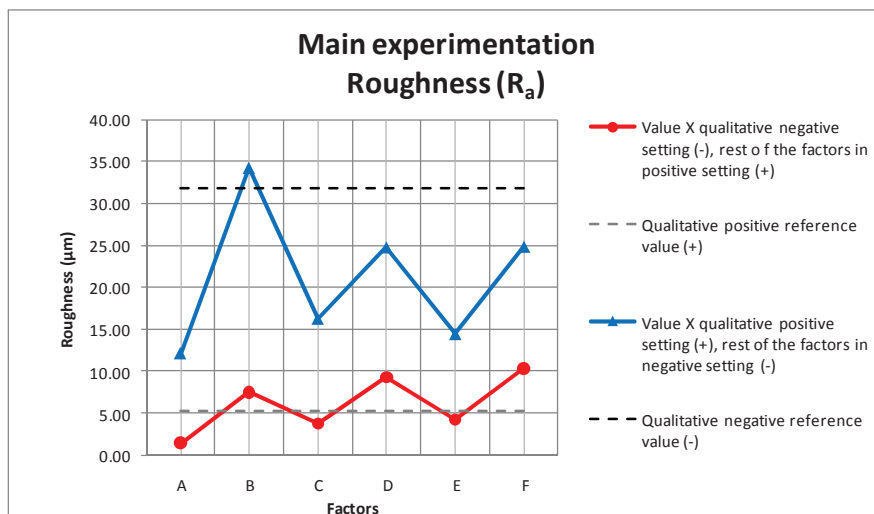


Figure 6: Roughness R_a results of the Shainin main experimentation

Tab. 6: Roughness R_a results of the Shainin main experimentation

Main experimentation Roughness R_a (μm)					Analysis		
Factors	Combination	Results	V_+	V_-	%	Variation average (%)	Conclusion
		[μm]	[μm]	[μm]			
A Laser power	AR+	1.43	5.29		-73	67	1° Red X
	A,R-	12.19		31.76	-62		
B Repetition rate	B,R+	7.48	5.29		42	25	less relevant
	B,R-	34.28		31.76	8		
C Burst-mode	C,R+	3.76	5.29		-29	39	2° Red X
	C,R-	16.28		31.76	-49		
D Focus position (from surface)	D,R+	9.27	5.29		75	27	less relevant
	D,R-	24.80		31.76	-22		
E Scanner feed rate	E,R+	4.18	5.29		-21	38	3° Pink X
	E,R-	14.48		31.76	-54		
F Hatch	F,R+	10.31	5.29		95	37	less relevant
	F,R-	24.87		31.76	-22		

6. Conclusions

The analysis of burst-mode laser ablation by modern quality tools accelerates the identification of significant parameters. Reducing the experimentation time and the number of experiments, it is attractive to the research of new materials and applications.

This paper describes an approach for the application of quality tools, e.g., Ishikawa's diagram and Shainin's analysis of parameter impact to evaluate their degree of influence. Among the conclusions, laser power and burst-mode have a strong direct influence to ablation rate. Moreover, these afore mentioned parameters offer as well, a high influence on the roughness. Second to laser power, burst-mode presents also a high influence on the roughness showing a high variation average in both directions (high and low). Nevertheless, the number of bursts has to be reconsidered due to the fact that the chosen number for this study (8 bursts) did not show an improvement of the surface quality but the contrary effect. In addition, focus position and hatch distance performs little influence to ablation rate and roughness and they can be kept constant for future experimentation.

In short, these results state that there is a direct relationship among quality and economy. Therefore, the increase of laser power combined with the appropriated burst-mode not only enables high ablation rates but also surface quality. For the next scientific steps, a detailed study can be concentrated on different levels of burst-mode and laser power, and "Pink X's" can be included. Lastly, interaction effects of the factors must be an important point to be considered in future studies.

Acknowledgements

The authors wish to thank Mr. Hendrik Vogel for his support in this study, and CONACYT (Consejo Nacional de Ciencia y Tecnología of México) for its financial support given under its Ph.D. Scholarship program.

References

- [1] Meijer, J., Du, K., Gillner, A., Hoffmann, D., Kovalenko, V. S., Masuzawa, T., et al.: Laser Machining by short and ultrashort pulses, states of the art and new opportunities in the age of the photons. In: CIRP Annals – Manufacturing Technology, Vol. 51, 2 (2002), 531-550
- [2] Dirscherl, M.: Ultrakurzpulslaser - Grundlagen und Anwendungen. BLZ Anwenderfibel, Erlangen, 2 (2005), 10-20
- [3] Hartmann, C., Gillner, A.: Investigation on Laser Micro Ablation of Steel using PS-IR Pulse Burst. In: ICALEO Congress Proceedings – Laser Microprocessing Conference, Orlando, 2007, 38-44
- [4] Gillner, A., Dohm, A., Hartmann, C.: High quality laser machining for tool and part manufacturing using innovative machining systems and laser beam sources. In: 3rd. International Conference High Performance Cutting, Dublin 2008, 199-208

- [5] Müller, D., Haloui, H., Klimt, B., Knappe, R., Nebel, A.: Burst-Mode Micromachining with High Power PS Lasers. In: ISL 2010, Chemnitz, 2010
- [6] Pfeifer, T.: Quality Management - Strategies, Methods, Techniques. Hanser, München, 3 (2002), 347-348, 374-378
- [7] DIN V 32540.: Laser Beam Removing – Thermal removing with laser beam – Definitions , Influence factors, procedures. Beuth, Berlin, 1997
- [8] Emmelmann, C.: Laser ablation – Guest lecture at the Hamburg University of Technology, Institute of Laser and System Technologies, Hamburg, 2010
- [9] Lumera Laser GmbH: Hyper Rapid 50 – High Power Industrial Picosecond Laser – Specification Sheet, Kaiserslautern, 2010
- [10] Beckford, J.: Quality: A Critical Introduction. Routledge, New York 2 (2002), 249-250
- [11] Hering, E., Triemel, J., Blank, H.-P.: Qualitätsmanagement für Ingenieure. Springer, Berlin, 5 (2003), 227-228
- [12] Bhole, K. R.: World Class Quality – Using Design of Experiments to make it happen. Amacom, New York, 1991
- [13] Lorenz, A., Rehme, O., Emmelmann.: Statistische Versuchsplanung in der Lasermaterialbearbeitung. In: Photonik 3 (2003), 93-95
- [14] Emmelmann, C., Petersen, M., Goeke, A.: Laser Freeform Fabrication for Aircraft Applications. In: Proceedings of the Fifth International WLT-Conference on Lasers in Manufacturing 2009 (LiM 2009), AT-Fachverlag GmbH, Munich, 2009, 171-174