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The application of the random balance method in laser machining of metals

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ABSTRACT

Features peculiar to laser technology offer some advantages over more traditional processes, but, like all processes, it has its limitations. This article studies the limitations of laser machining of metals, and quantifies, through an experimental design method, the influence of operating parameters on productivity and on the quality of the machined surface. Three study materials were used: an aluminium alloy, stainless steel and a titanium alloy. An initial reading of the results indicates that productivity depends mainly on the frequency of the laser pulse and that the aluminium alloy behaves differently from the other two. The quality of the machined surface, judged here by roughness, was likewise dependent on pulse frequency and, to a lesser degree, on sweep speed. Surface roughness was minimized by increasing the pulse frequency and reducing the sweep speed. The experimental results were accurately predicted by simple polynomial models.

1. Introduction

Laser machining of metals has some advantages nowadays over more traditional, non-laser, processes. For example, there is greater flexibility of use, no mechanical contact with the surface, a reduction in effluents (as no acid or solvent is used) and a fine accuracy of machining, even with complex forms as with those of injection moulding.

The many physical mechanisms involved in the interaction between the laser beam and the material make the procedure particularly complex. With a view to perfecting the machining process, research has been carried out in recent years on various materials to determine the effects of the operational parameters. Some authors (Knowles et al., 2005; Meijer, 2004; Tuersley et al., 1998a,b) have demonstrated that results of a high quality can be obtained through a well-judged choice of operational parameters. One of the problems yet to be resolved is to find a correlation between productivity and the eventual quality of the machined surface. By using an experimental design method, Lallemand (Lallemand et al., 2000) has shown that the three factors of pulse frequency, position of the focal point and machining speed strongly influence the geometry and quality of the etching. Other studies (Qi et al., 2003; Kaldos et al., 2004) have proved that pulse frequency is still the most influential factor in laser machining.

The aim of the study set out below is to demonstrate the limitations of laser machining of metals and to show which process control parameter influence productivity (machining rate) and surface quality (degree of roughness) the most.

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Table 1 – Chemical composition of the aluminium alloy AA6056

Elements of the alloy (mass%)	
Si	0.82
Fe	0.07
Cu	0.55
Mn	0.57
Mg	0.69
Zn	0.17
Ti	0.02
State	T4

Table 2 – Chemical composition of the stainless steel X3CrNi18-10

Elements of the alloy (mass %)	
C	0.03
Cr	18
Ni	10
Mn	2 (max)
Si	1 (max)

Table 3 – Chemical composition of the titanium alloy TA6V

Elements of the alloy (mass%)	
Al	5.5,. . .,6.75
V	3.5,. . .,4.5
O	0.2 (max)
Fe	0.4 (max)
H	0.015 (max)
C	0.1 (max)
N	0.05 (max)

The data were analysed with the experimental design method (Montgomery, 1991; Nichici et al., 1996; Cicală, 1997, 1999). In this way, a large number of factors can be studied for a relatively small number of tests, without compromising the estimates of the effects of each factor.

2. Experimental procedure and results

For this study, three materials were selected: a 6056 T4 aluminium alloy, stainless steel X3CrNi18-10 and a TA6V titanium alloy, as shown in Tables 1–3.

The tool used in the experiments was a Q-switch Nd:YAG laser provided with a marking trigger ($\lambda = 1.064\,\mu m$) and equipped with a galvanometric head.

Laser machining was carried out on geometrically similar specimens (Fig. 1a) with laser sweeping in the zone to be machined. To gain an easily characterized print, sweeping was done 18 times with alternating passes at 0° and 90° (Fig. 1b). The machining produced a square of 5 mm × 5 mm on each specimen for the operational parameters that were applied.

Table 4 – Process controls parameters and their levels

Parameter levels	I (A)	f (Hz)	v (mm s^{-1})	ls (μm)
1	39	1500	6	10
2	44	3500	9	50
3	49	5500	12	90
4	–	7500	15	–
5	–	9500	18	–

For each experiment, the specimen was weighed before and after machining, and the machining time was recorded. In that way, the machining rates, in mass and volume, could be calculated.

The common experimental conditions to all the tests were:

- laser beam wavelength 1064 nm;
- laser beam was delivered thru a diaphragm with 4 mm in diameter;
- laser beam spot diameter is 300 μm on the surface of the targets, with normal incidence;
- pulses width with an average duration of 400 ns.

The data were analysed with the experimental design method (Montgomery, 1991; Nichici et al., 1996; Cicală, 1997, 1999). In this way, a large number of factors can be studied for a relatively small number of tests, without compromising the estimates of the effects of each factor.

The objective functions to be determined were:

- material removal rate: MRR (mm^3 min^{-1});
- roughness of the machined surface: Ra (μm).

On the basis of work done in the laboratory, it was decided to adopt the following as process control parameters:

- intensity of current excitation of diodes: I (A);
- frequency of the laser pulses: f (Hz);
- sweep speed: s (mm s^{-1})
- line-spacing: ls (μm).

Three separate levels for intensity and line-spacing and five separate levels for frequency and sweeping speed were established (Table 4). The levels was distributed uniformly over the work area and spaced equally in their individual machine settings. The design matrix of experiments was identical for the

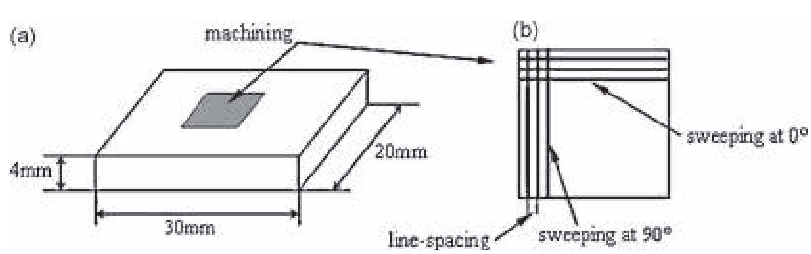

Fig. 1 – The specimens geometry (a) and laser cross sweeping (b).

Table 5 – Random balance design matrix and observed values of objective functions

Test no.	Process control parameters				Observed values of objective functions for three materials					
	I (A)	f (Hz)	s (mm s^{-1})	ls (μm)	AA6056		X3CrNi18-10		TA6V	
					MRR (mm^3 min^{-1})	Ra (μm)	MRR (mm^3 min^{-1})	Ra (μm)	MRR (mm^3 min^{-1})	Ra (μm)
1	3	5	2	1	0.0036	2.60	0.7574	5.87	1.2403	3.44
2	1	5	1	3	0.0073	1.46	0.9572	7.10	0.8114	2.57
3	2	1	5	1	0.9811	13.71	0.5531	14.02	0.5732	7.05
4	1	2	4	2	0.3655	11.18	0.9163	10.93	1.0005	7.10
5	3	1	2	1	0.9619	6.50	0.6260	13.76	0.6641	3.32
6	3	4	3	1	0.0047	5.44	0.8253	2.76	1.0131	2.82
7	1	5	2	2	0.0178	1.65	0.9387	6.03	0.8012	6.16
8	1	3	3	1	0.0078	2.53	0.7523	11.76	1.0107	12.66
9	2	1	4	2	0.9105	8.77	0.5823	13.14	0.5312	7.68
10	3	4	3	2	0.0077	0.94	1.0489	10.96	1.1433	1.22
11	2	4	1	3	0.0073	2.06	1.0643	1.65	1.1032	1.80
12	1	3	5	3	0.0198	0.62	0.9466	11.45	0.9208	4.51
13	3	3	5	3	0.0001	3.70	1.2601	8.92	1.3521	6.48
14	2	2	1	2	1.1993	9.58	1.1605	12.30	1.2117	5.21
15	2	2	4	3	1.0647	10.70	1.2844	15.33	1.2041	13.49

three materials. In this way, performance could be compared directly.

The random balance design matrix (Nichici et al., 1996; Cicală, 1997) consisted of 15 tests and was characterized by a normalized appearance of the levels of the factors (five times for the factors with three levels, and three times for the factors with five levels). The distribution of these levels was randomized (Table 5). By reducing the number of tests, the importance of the effects of each factor can be characterized with this technique.

For each parameter combinations were processed three samples and the experimental tests were carried out in random order. The average results values for material removal rate and surface roughness corresponding to each test are presented in Table 5.

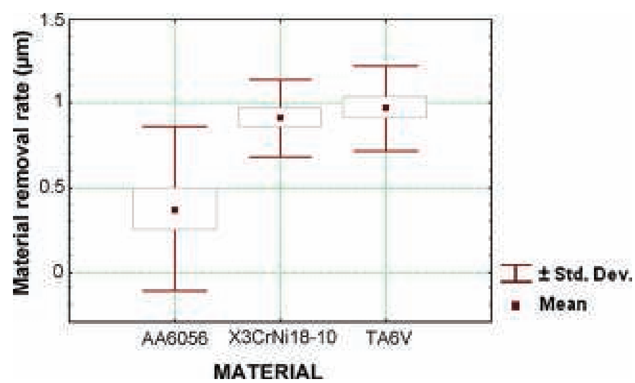

Fig. 2 – Average material removal rate and standard deviation.

3. Analysis of the results

The following conclusions can be drawn from an analysis of the results:

- The stainless steel and the titanium alloy have similar material removal rates (Fig. 2). The aluminium alloy has a lower average material removal rate and a wider dispersion of results. Overall, the aluminium alloy is affected more than the other two by at least one of the process control parameters.
- As for surface roughness, it is clear that for stainless steel is greater than for the other two alloys (Fig. 3), and that the dispersion of the results is similar for all three.

Fig. 4 shows clearly that the stainless steel and the titanium alloy have a similar behaviour to each other and different from the aluminium alloy, for which nine combinations of parameters over the 15 tests gave negligible values for material removal rate.

The effects on material removal rate induced by the various factors were measured by means of the random balance method for a confidence level of 95%. These results are put together in Tables 6 and 7. A rank order was attributed to each influence factor in order to realise a hierarchical classification. The significance of factors was established by using a significance level of 0.05. Concerning material removal rate, not all factors are significant for this significance level as are I and s for X3CrNi18-10 and as s and ls for TA6V, from where the 3rd

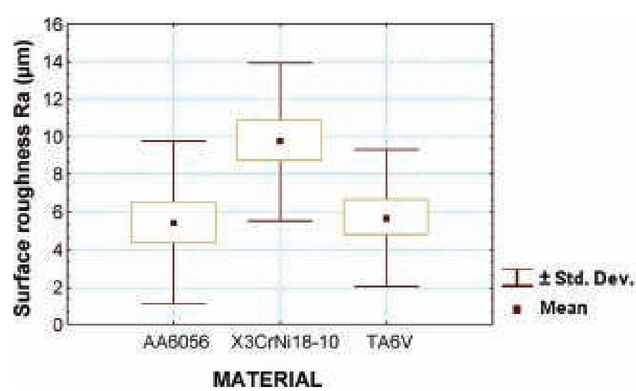

Fig. 3 – Average surface roughness and standard deviation.

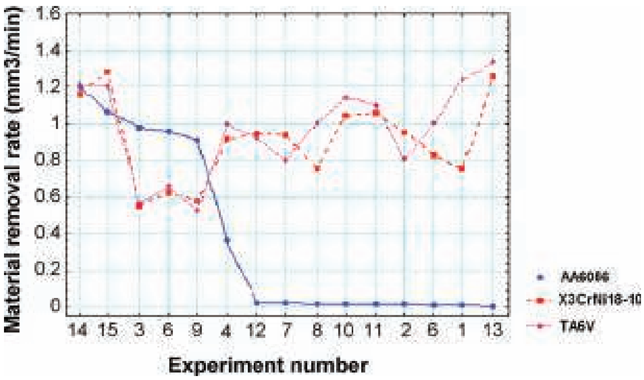

Fig. 4 – Levels of the material removal rates of the three materials.

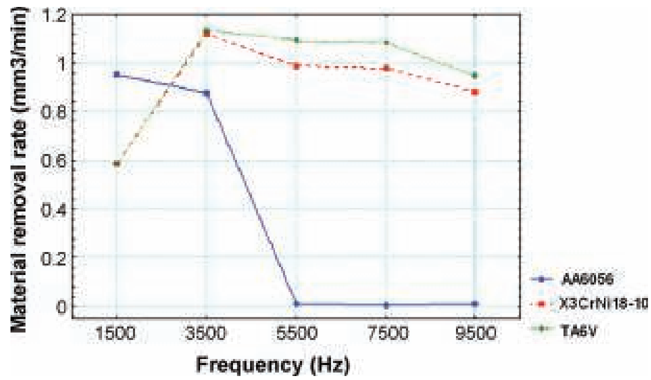

Fig. 5 – Material removal rate as a function of frequency.

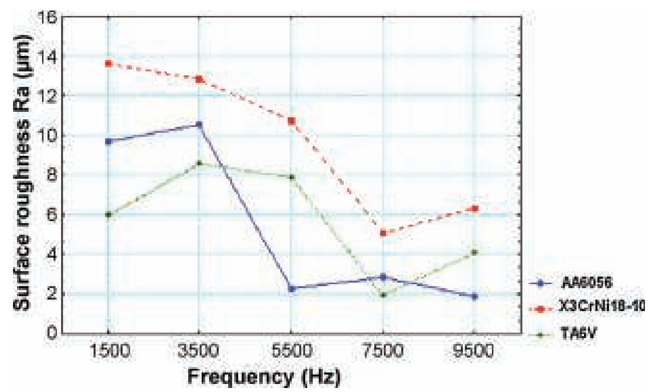

Fig. 6 – Surface roughness as a function of frequency.

and 4th rank order (Table 6). In the case of AA6056 all factors have a significant influence on the material removal rate, for a significance level of 0.05. Concerning surface roughness, it was establish, that for the same significance level (0.05), all factors are significant for all three materials (Table 7)

It is clear that, for all three alloys, it is frequency that makes the greatest difference – over half the total effect – to the material removal rate and to the surface roughness as shown in Tables 6 and 7.

As shown in Fig. 5 the evolution of material removal rate as a function of frequency is almost similar for both the stainless steel and titanium alloy. The maximum material removal rate was achieved at a frequency of around 3500 Hz, followed by a slight decrease when the frequency goes higher. On the other hand, the behaviour of the aluminium alloy (Fig. 5) is different, however, the maximum material removal rate being reached at lower frequencies ($f \in$ [1500 Hz; 3500 Hz]) followed by a sharp decrease, with measured values tending towards zero.

From these results simple polynomial models can be formulated to estimate the material removal rates for the stainless steel and the titanium alloy. The general form of model is:

$$Y = b_0 + b_1 X_1 + b_2 X_2 + b_{11} X_1^2 \quad (1)$$

Table 6 – Effects of the process control parameters on material removal rate

Metal alloy	Result	Process control parameters			
		f	v	I	ls
AA6056	Overall effect (mm^3 min^{-1})	0.94	0.26	0.22	0.05
	Parameter influence rank	1	2	3	4
X3CrNi18-10	Overall effect (mm^3 min^{-1})	0.53	0.11	0.15	0.21
	Parameter influence rank	1	4	3	2
TA6V	Overall effect (mm^3 min^{-1})	0.55	0.1	0.26	0.05
	Parameter influence rank	1	3	2	4

Table 7 – Effects of the process control parameters on surface roughness

Metal alloy	Result	Process control parameters			
		f	v	I	ls
AA6056	Overall effect (µm)	8.58	2.17	0.81	1.34
	Parameter influence rank	1	2	4	3
X3CrNi18-10	Overall effect (µm)	8.52	2.59	0.34	1.19
	Parameter influence rank	1	2	4	3
TA6V	Overall effect (µm)	6.65	3.35	2.22	1.48
	Parameters influence rank	1	2	3	4

Table 8 – Estimated values of the model coefficients[a]

Metal alloy	Model coefficients values			
	b_0	b_1	b_2	b_{11}
X3CrNi18-10	0.33	0.17	0	−0.01
TA6V	−0.68	0.3	0.02	−0.02

[a] frequency expressed in kHz, line-spacing in µm, intensity in A, and material removal rate in $mm^3 min^{-1}$.

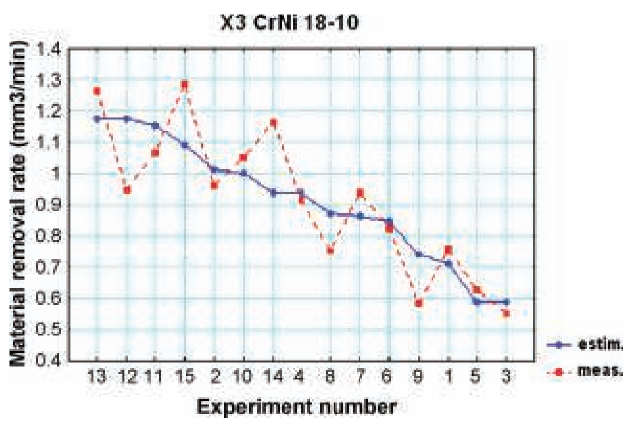

Fig. 7 – Comparison between the measured and estimated values of material removal rate for stainless steel.

where Y is the material removal rate, X_1 the parameter of greatest influence (here, frequency) and X_2 is the second most influential parameter. The coefficients b_0, b_1, b_2 and b_{11}, calculated by the method of least squares (Nichici et al., 1996; Cicală, 1999), are shown in Table 8.

Despite the simplicity of this model, it is clear that there is a very good correlation, between the measured and estimated values (Figs. 7 and 8) statistically accepted for a confidence level of 99%. The mathematical model is adequate for the satisfactory R^2 value. Correlation coefficient (R^2) for X3CrNi18-10 and TA6V was calculated to be 0.8461 and 0.8393, respectively.

As for surface roughness, the most important parameter is still frequency, followed by sweeping speed, and that applies to all three materials. The cumulative effect of these two factors comes to more than 70% for the interaction between the beam

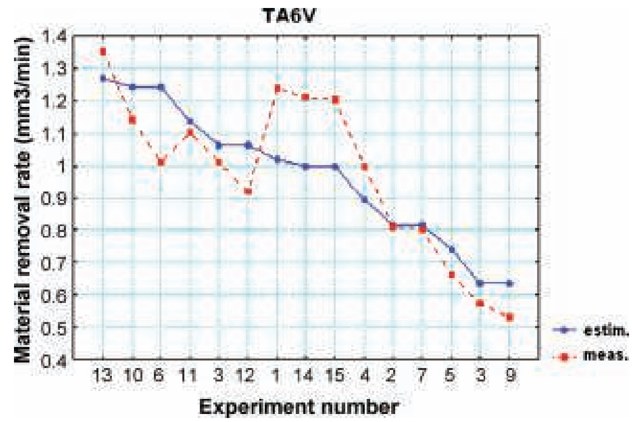

Fig. 8 – Comparison between the measured and estimated values of material removal rate for titanium alloy.

and the material (83% for AA6056, 88% for X3CrNi18-10, and 73% for TA6V).

Overall, surface roughness changes inversely to frequency (Fig. 6) and increases with sweep speed. For this reaction, the behaviour of the three alloys is similar, though surface roughness for the steel is still greater than for the other two alloys (Figs. 3 and 6).

Surface appearance and quality as a function of employed parameters can be observed, qualitatively at least, by using an optical and electronic microscope.

For the stainless steel:

- Fig. 9 shows the typical surface appearance with small roughness (Ra < 4 µm). At the limit of each laser sweep the material projections is observed as well as the presence of slag on all surface (Fig. 9a). Analysing the material microstructure on surface, any alteration is not observed (Fig. 9b).
- Fig. 10 shows a typical surface appearance with high roughness (Ra > 10 µm). Substantially material projections are noticeable, as well as (Fig. 10a) gaps whose spacing is comparable with that of the laser spot diameter (horizontal direction). There is a large molten pool, and the molten material can be seen to have been pushed back behind the laser shot. The surface microstructure has not been modified by laser machining (Fig. 10b).

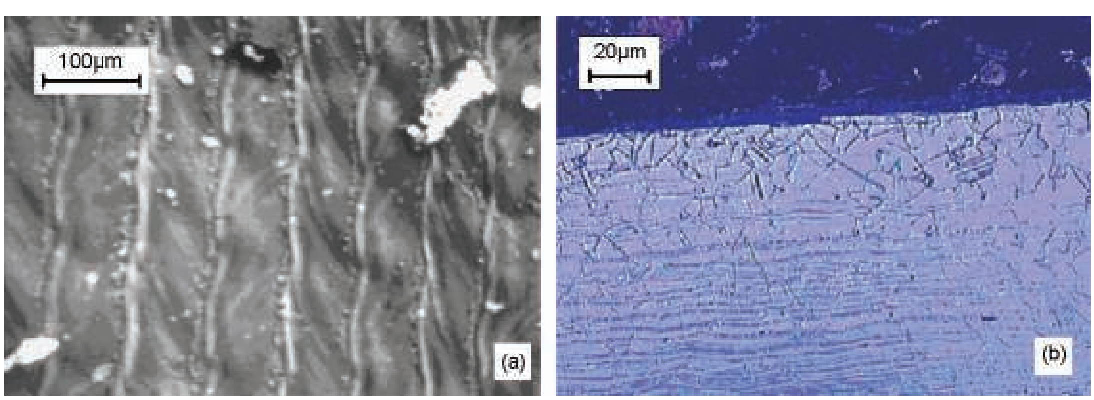

Fig. 9 – SEM image (200×) (a) and optical microscope image (b) of specimen 11 of X3CrNi18–10.

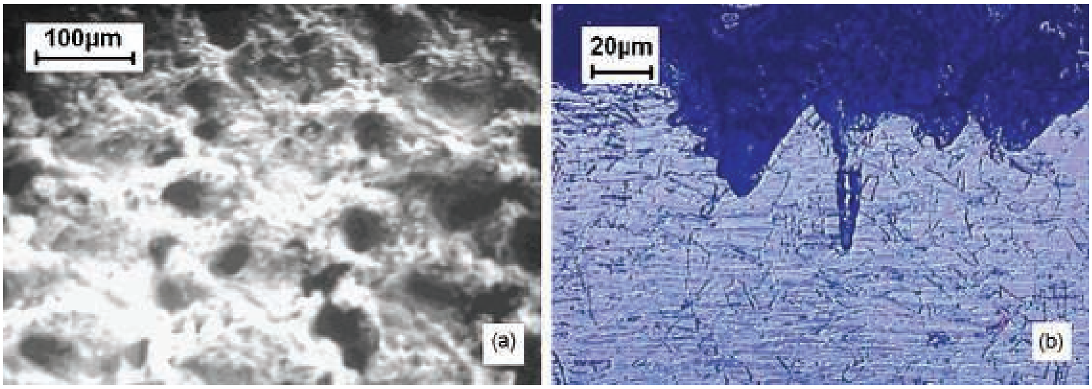

Fig. 10 – SEM image (200×) (a) and optical microscope image (b) of specimen 14 of X3CrNi18–10.

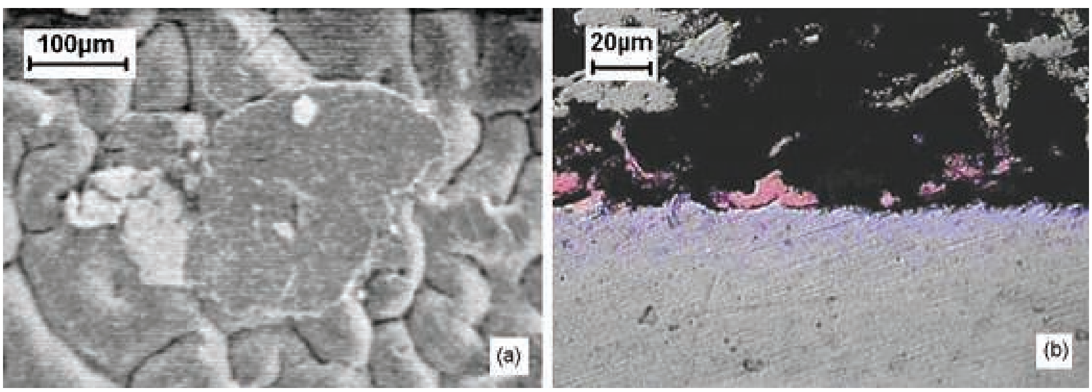

Fig. 11 – SEM image (200×) (a) and optical microscope image (b) of specimen 7 of AA6056.

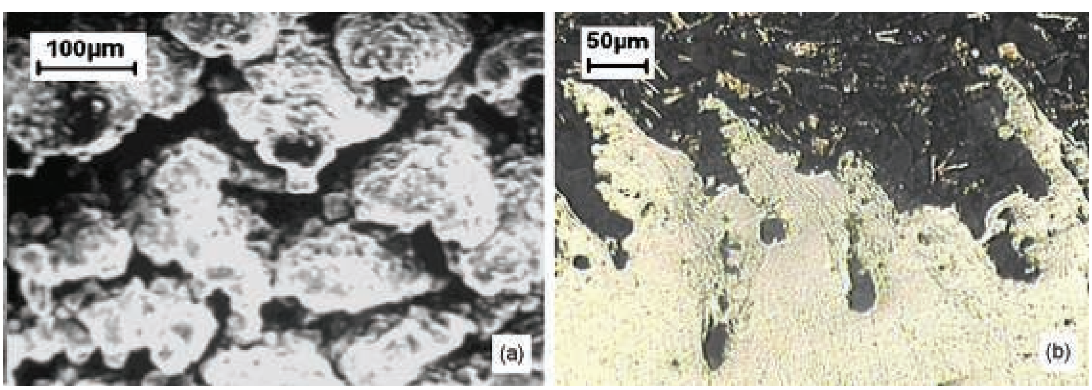

Fig. 12 – SEM image (200×) (a) and optical microscope image (b) of specimen 3 of AA6056.

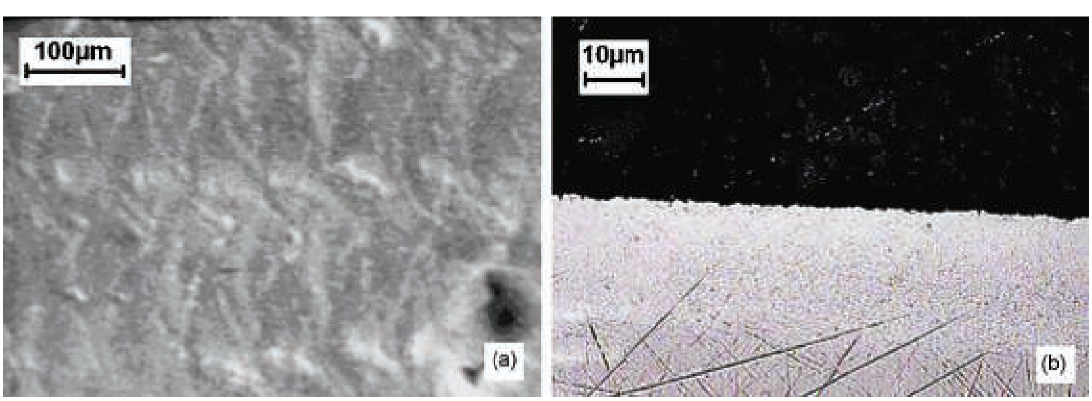

Fig. 13 – SEM image (200×) (a) and optical microscope image (b) of specimen 10 of TA6V.

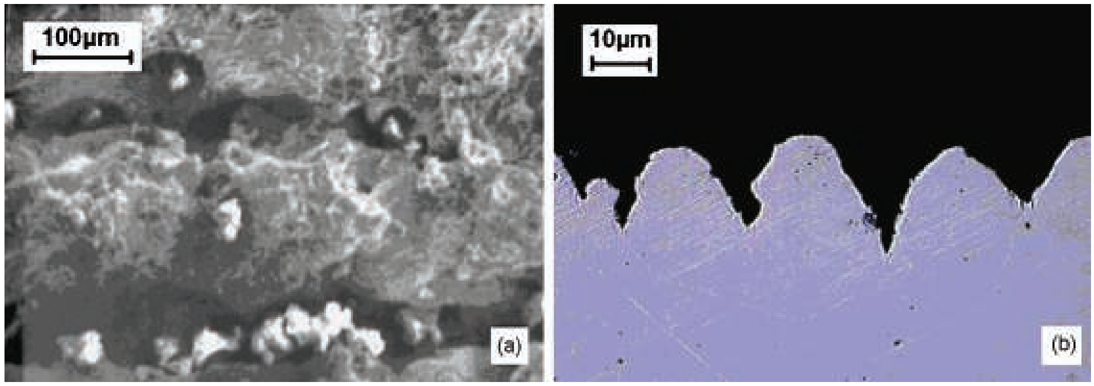

Fig. 14 – SEM image (200×) (a) and optical microscope image (b) of specimen 15 of TA6V.

For the aluminium alloy AA6056:

- Fig. 11 shows the typical surface appearance with small roughness (Ra < 4 μm); slag and the joints of alloy grains are observed.
- Fig. 12 illustrates the typical surface appearance with high roughness (Ra > 10 μm); the molten pool has been substantially pushed back behind each laser pulse (Fig. 12b). The gap between the fusion and vaporization temperature is very important (≈1900 K), from where the possibility of an important melted pool formation.

For the titanium alloy TA6V:

- Fig. 13 shows the typical surface appearance with small roughness (Ra < 4 μm).
- Fig. 14 shows the typical surface appearance with high roughness (Ra > 10 μm); the laser sweeps are strongly marked. The slag is present (Fig. 14a) as result of melted material projection during the laser machining and the grooves formed during the cooling of non-ejected material are observed (Fig. 14b).

While the border conditions for aluminium alloy machining (material removal rate) can easily be observed in Fig. 4, for two other alloys is less obvious.

That was the reason that the results for the rank order of the process control parameters were verified and confirmed by complementary tests for conditions estimated as border (maximum and minimum material removal rates for the X3CrNi18-10 and the TA6V). The experimental designs matrix and their results are shown in Tables 9 and 10.

Table 9 – Complementary tests for the X3CrNi10-18 to confirm the border conditions for material removal rate

Test no.	Estimated results	Fixed parameters		Variable parameters		Measured MRR ($mm^3\,min^{-1}$)
		f (Hz)	ls (μm)	s ($mm\,s^{-1}$)	I (A)	
1	High MRR	3500	100	9	40	1.13
2		3500	100	9	45	1.15
3		3500	100	18	40	1.02
4		3500	100	18	45	1.01
5	Low MRR	1000	50	18	40	0.36
6		1000	50	12	35	0.31
7		1000	10	12	40	0.11
8		1000	10	18	35	0.09

Table 10 – Complementary tests for the TA6V to confirm the border conditions for material removal rate

Test no.	Estimated results	Fixed parameters		Variable parameters		Measured MRR ($mm^3\,min^{-1}$)
		I (A)	f (Hz)	s ($mm\,s^{-1}$)	ls (μm)	
1	High MRR	45	3500	9	10	1.32
2		45	3500	9	100	1.30
3		45	3500	6	10	1.26
4		45	3500	6	100	1.29
5	Low MRR	35	1000	12	10	0.41
6		35	1000	12	50	0.30
7		35	1000	18	10	0.37
8		35	1000	18	50	0.30

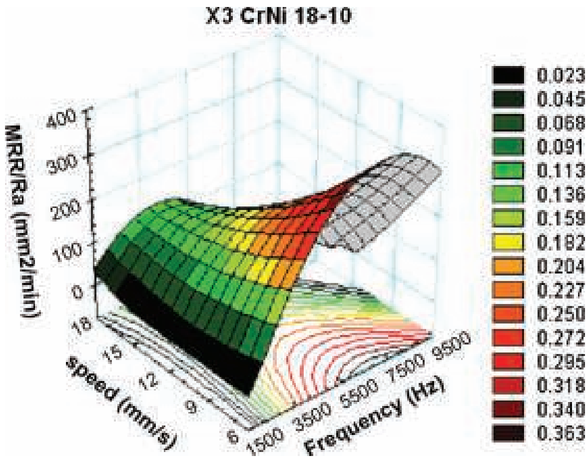

Fig. 15 – Optimal conditions representation of laser machining of stainless steel.

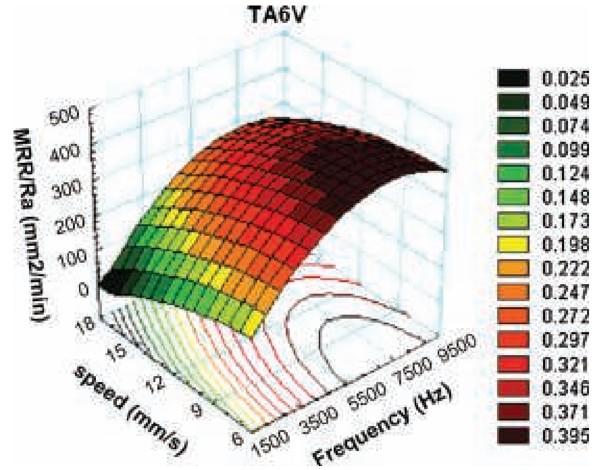

Fig. 16 – Optimal conditions representation of laser machining of titanium alloy.

It is clear from Table 9 that the estimates for the alloy X3CrNi18-10 are correct: the material removal rates are strongly influenced by pulse frequency (rank 1). The maximum values (between 1 and 1.15 $mm^3\,min^{-1}$) were obtained with a frequency of 3500 Hz and the minimum values (between 0.1 and 0.4 $mm^3\,min^{-1}$), with a frequency of 1000 Hz. These results are independent of the values for sweep speed (rank 4) and for line-spacing (rank 3).

It is clear from tests 1–4 of Table 9 that, if the factors of frequency (f) and line-spacing ls are fixed, merely a change of sweep speed and of intensity does not lead to any significant change in the material removal rate (about 0.1 $mm^3\,min^{-1}$). If a change in line-spacing (rank 2, tests 5–8 from Table 9) is then added, that produces an increase in the material removal rate up to 0.25 $mm^3\,min^{-1}$. Finally, a change in frequency (rank 1) can cause an increase in the material removal rate up to 0.8 $mm^3\,min^{-1}$.

The estimates for the rates for the titanium alloy TA6V are also confirmed (Table 10): the volume removal rates are strongly influenced by pulse frequency (rank 1) and by intensity (rank 2). The maximum values (about 1.3 $mm^3\,min^{-1}$) or minimum values (between 0.3 and 04 $mm^3\,min^{-1}$) were obtained with the pairing of frequency and intensity (f and I), independently of the values for sweep speed (rank 3) and of those of line-spacing (rank 4).

It is very often the case that, in machining process, the ideal is to maximize the speed of the task while still ensuring a good quality for the surface. That is why it is important to consider the two objective functions of material removal rate and surface roughness together. The optimum conditions for the task can be identified from the results of Table 5 (see also Figs. 15 and 16). Again, it is obvious that the stainless steel and the titanium alloy have a similar behaviour to each other: for both, the relationship between material removal rate and surface roughness is at its optimum for the same pair of process parameters, namely, frequency at 7000 Hz and speed at 6 $mm\,s^{-1}$.

In view of the "threshold" behaviour of the aluminium alloy (in relation to pulse frequency), a choice must be made between minimizing surface roughness, at high frequencies (≈7500 Hz), and maximizing material removal rate, at low frequencies ($f \in [1500, 3500]$ Hz).

4. Conclusions

On the basis of the above study, a rank order can be established in respect of the desired objective, whether material removal rate or surface roughness, for all three alloys, AA6056, X3CrNi18-10 and TA6V.

From a synthesis of the results, similarities in the behaviour of the three alloys can be advanced:

- Material removal rate:
  - In the experimental field under investigation, material removal rate depends mainly on the frequency of the laser pulses, the highest material removal rate (~1.3 $mm^3\,min^{-1}$) being recorded for a frequency of 3500 Hz.
  - At high frequencies ($f \geq 5500$ Hz) the behaviour of the aluminium alloy, AA6056, differs from that of the other two. When $f \geq 5500$ Hz, the material removal rate drops sharply to almost zero, whereas the material removal rate for the stainless steel X3CrNi18-10 and titanium alloy TA6V decreases gradually as frequency increases. For these two alloys, an accurate estimate of the experimental result can be obtained from simple polynomial models.
- Surface roughness:
  - The surface roughness of the machined surface depends mainly on pulse frequency and, secondarily, on sweep speed. The lowest levels of roughness (Ra ≈ 2 μm) were obtained with the highest frequencies ($f \geq 7500$ Hz) and with low sweep speeds. In general, the roughness recorded for the steel was greater than that measured on the titanium and aluminium alloys.
  - For operational conditions conducive to the formation of a substantial melted pool, the surface roughness becomes high (Ra > 10 μm) as a consequence of the solidification of the non-ejected molten material.

Finally, for the stainless steel and titanium alloy, optimum values can be shown for the relationship between material removal rate and surface roughness, namely by the pair of frequency at 7000 Hz and speed at 6 mm s^{-1}.

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