Experimental investigation and optimisation of laser direct part marking of Inconel 718

C. Leone\textsuperscript{a,d,*}, E. Bassoli\textsuperscript{b,d}, S. Genna\textsuperscript{c,d}, A. Gatto\textsuperscript{b,d}

\textsuperscript{a}Department of Engineering, University of Campania Luigi Vanvitelli, Via Roma 29, Aversa (Ce) 81031, Italy
\textsuperscript{b}Department of Engineering ‘Enso Ferrari’, University of Modena and Reggio Emilia, via Vivarelli 10, Modena 41125, Italy
\textsuperscript{c}Department of Enterprise Engineering Mario Lucertini, University of Rome Tor Vergata, Via del Politecnico 1, Rome 00133, Italy
\textsuperscript{d}CIRTIBS Research Centre, University of Naples Federico II, P.le Tecchio 80, Naples 80125, Italy

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A B S T R A C T

Many industries need product identification; laser marking is suitable to produce any kind of symbol, data matrix or bar code on parts. Consequently, the most important requirement for marking acceptance is, doubtless, the mark readability. The present study deals on the effect of process parameters on the laser marking of Inconel 718, with the aim to find a relation between the process parameters and mark characteristics in term of both mark geometry and readability. To this aim, laser markings, under different process conditions, were performed on Inconel 718 sheets, adopting a 30 W Q-switched Yb:YAG laser. The mark geometry was acquired by a 3D surface profiling system. Optical microscopy and SEM analysis were also performed on groove sections. In order to evaluate the readability of the marks, Weber contrast was calculated and adopted. The mark characteristics have been investigated by mean of statistical methodology (ANalysis of Variance and Response Surface Methodology) and related to the process parameters. Furthermore, Master Response Optimisation methodology was adopted to individuate the optimal process conditions. It was found that mark geometry and the Weber contrast are mainly affected by the average power and the energy input per mark-length. Moreover, operative conditions allowing for maximum readability, yet without excessive increase in burr height, were also determined.

1. Introduction

The complete identification and traceability of items that leave the manufacturing process should be ensured in order to reduce the trade of counterfeit goods, improve security and efficiency and acquire information in real time for market analysis [1]. This is especially true in some industrial sectors (such as aerospace, aviation, automotive and medical), where the products must meet specific requirements and standards. As a consequence, the product identification must be of the highest quality to ensure traceability, safety and a reliable performance. Therefore, emphasis has been given to product identification and permanent marking without inks or adhesives. Bar code printing and Direct Part Marking (DPM or machine-readable identification) can be performed through a variety of manufacturing processes, such as: punches, microdot, scribing or electric discharge pencil etcher. However, laser marking applications are becoming the norm in most manufacturing fields since they offer several advantages, such as: non-contact working, high repeatability, high scanning speed, a mark width comparable to the laser spot dimension, high flexibility and high automation of the process itself [2–5]. Because of the need for identification in the previously described industry sectors, the demand for laser job shops is likely to increase in the future [6].

Laser marking is the preferred method of performing DPM to attain permanent and highly contrasted superficial inscriptions on a wide variety of materials, ranging from glass [7], ceramics [8–11], organic materials [12–18] and, of course, metals [3,4,19–22]. However, the criteria for marking acceptance may take in account many factors, such as: mark geometry, heat-affected zone extension, presence of micro-cracks, durability under harsh operational conditions and, last but not least, readability [3].

Two processes are necessary before a barcode or mark can be successfully read: one is the formative period, which involves laser-material interaction, and the other is the auto-identification process by means of the direct interaction between the scanner and the written characters [5].

Readability is used to describe how well a reader can decode a symbol and depends on the mark characteristics (geometry, surface roughness, oxide presence) and measuring techniques. Several different factors should be addressed to create a good quality code or mark: contrast, size and mark consistency. A good contrast increases the possibility of

\textsuperscript{*} Corresponding author at: Department of Engineering, University of Campania Luigi Vanvitelli, Via Roma 29, Aversa (Ce) 81031, Italy.
E-mail addresses: claudio.leone@unicampania.it, claleone@unina.it (C. Leone).

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reading at longer distances and reduces the chance of noise interference [23].

Readability is usually evaluated considering the Symbol Contrast (SC) value. This is the difference between the arithmetic means of the darkest 10% and lightest 10% of the image pixels [24,25]. The ISO Symbol Contrast grade scale ranges from 0.0 to 4.0.

However, in laser marking operation, since the readability is affected by the marking characteristics, the setting of the laser parameters remains a critical issue. From the literature [19–21], it results that the main processing parameters affecting the laser marking are:

- average power;
- scan speed (i.e. the marking velocity);
- pulse frequency.

Nevertheless, the relation between the process parameters and the marking characteristics (geometry and readability) involves complex phenomena. As a matter of fact, permanent marking can be obtained by three different mechanisms: laser colouring, favoured by a low-power beam to give rise to surface oxidation; laser etching, requiring a more powerful laser to melt the surface of the substrate; laser engraving, involving an even higher power to vaporize the material surface [26,27]. Generally speaking, the three mechanisms differ in the required power level (increasing from colouring to engraving), however the power threshold levels determining the change in interaction mechanism strongly depend on the worked material.

The present study deals with the effect of process parameters on the laser marking of Inconel 718, with the aim to find a relation between the process parameters and marking characteristics: geometry and readability. To this aim, laser marking under different process conditions was performed on Inconel 718 sheets, 1 mm in thickness, adopting a 30 W Q-switched Yb:YAG fiber laser. The mark geometries were acquired by a 3D surface profiling system. Optical microscopy and SEM analysis were also performed on some sections. In order to evaluate the readability of the marks, Weber contrast was measured. Then, the experimental data obtained were analysed by statistical methodology (ANalysis of VAriance and Response Surface Method) in order to determine the correlation between process conditions and mark characteristics. In addition, Master Response Optimisation (MRO) was adopted to identify the optimal process conditions. Future applications of the research regard the possibility to achieve laser marks that offer the best compromise between good contrast and restrained geometrical features (i.e. a limited burr height and mark depth). The latter would have an important industrial impact, in all the applications requiring marks with good contrast but causing the minimum possible damages (i.e. geometrical change) to the parts.

2. Material, equipment and experimental procedures

2.1. Material

The investigated material was the Inconel 718 alloy (AMS 5962 or ASTM B637) in form of rolled sheets, 1 mm in thickness. Inconel 718 is a nickel-chromium alloy that combines a high-strength, with fatigue, creep, and corrosion-resistance. Thanks to its properties, Inconel 718 is adopted in a wide range of applications, such as: rings, casings and various formed sheet metal parts for aircraft and gas turbine engines, propellant tanks for rocket and cryogenic tanks, pump elements, F1 engines, nuclear reactors, fasteners and instrumentation parts. In Table 1 the chemical composition and the main properties of the Inconel 718 alloy are reported [28].

2.2. Laser equipment

The laser marking tests were carried out by adopting a laser system (LASIT Fly30 fiber) equipped with a Q-switched Yb:YAG fiber laser (IPG mod. YLP-RA 30-1-50-20-20). In the system, the laser beam is moved by means of a galvanometric scanner and focused by a 160 mm in length “flat field lens”, resulting in a beam diameter, at the focussing point, of about 80 μm, as declared by the producer. The laser system is controlled by a PC that allows the setting of the average power (Pa) by way of the percentage of maximum power, the pulse frequency (f) and the scan speed (Ss). In Table 2 the main characteristics of the laser system are reported, as declared by the producer.

As above mentioned, some authors reported that main processing parameters affecting the laser marking are the average power, the scan speed and the pulse frequency. Other authors, have pointed out the positive effect of high values of peak power or pulse overlapping [3,27], which allow better edge resolution and, therefore, better readability of the marked part to be obtained. Thus, it can be concluded that the characteristics of the marking also depend on the pulse parameters: pulse energy (Pe), pulse power (Pp), pulse duration (tp) as well as, by the overlapping factor (Of). The latter represents the overlapping percentage of two consecutive pulses. The pulse energy, the pulse power and the overlapping factor can be calculated by the following equations [29]:

\[
P_e = \frac{P_a}{f} \quad (1)
\]

\[
P_p = \frac{P_e}{t_p} \quad (2)
\]

\[
O[f\%] = \left[1 - \frac{(S_s/f)}{(d_s + S_s \times t_p)}\right] \times 100 \quad (3)
\]

where \(d_s\) represents the beam footprint on the component [30].

Before the experimentation, the laser source was characterised in term of average power by way of a power meter (FI50A-SH thermal head and a NOVA display from OPHIR). Then, the pulse energy and the pulse power were calculated according to Eqs. (1) and (2). In Fig. 1 the operative window of the adopted laser is reported in term of pulse power and pulse energy against the pulse frequency for three different average power values (in the figure the dots represent the tested conditions). To set the three power level, the percentage of maximum power was adjusted up to measure 10, 22.5 and 30 W on the power meter. It is worth noting that, since the adopted laser is able to release the same power at all the frequencies and works at constant pulse duration, the pulse energy and the pulse power differ by a constant (1/tp).

2.3. Experimental procedures

The selection of the process parameters (i.e. control factors) is a critical issue in statistical analysis, especially when the parameters are related one to each other. Since the best marking results can be achieved
Table 1
Chemical composition and main properties of Inconel 718 [28].

| Element | Ni<sup>a</sup> | Cr | Fe<sup>b</sup> | Nb-Cb | Mo | Ti | Co | Al |
|---------|----------------|----|-------------|------|----|----|----|----|
| %       | 50–55          | 17–21 | 17 | 4.75–5.5 | 2.8–3.3 | 0.65–1.15 | ≤ 1.0 | ≤ 0.20–0.80 |

| Element | Mn | Si | Cu | C | P | S | B | |
|---------|----|----|----|--|---|---|---|--|
| %       | ≤ 0.35 | ≤ 0.35 | ≤ 0.30 | ≤ 0.080 | ≤ 0.015 | ≤ 0.015 | ≤ 0.0060 | |

| Mechanical and Physical Properties | Value | Unit |
|-----------------------------------|-------|------|
| Ultimate Tensile Strength at 23 °C (650 °C) | 1375 (1100) | MPa |
| Tensile Yield Strength at Strain 0.2% and 23 °C (650 °C) | 1100 (980) | MPa |
| Elongation at Break at 23 °C (650 °C) | 25 (18) | % |
| Density | 8190 | kg/m³ |
| CTE, linear, at 20–100 °C | 13 | μm/m/K |
| Specific Heat | 0.435 | J/g · °C |
| Thermal Conductivity | 11.4 | W/m-K |
| Melting Point, solidus (liquidus) | 1260 (1336) | °C |

<sup>a</sup> includes cobalt.

<sup>b</sup> As remainder.

Table 2
Laser system characteristics.

| Characteristic | Symbol | Value | Unit |
|----------------|--------|-------|------|
| Wavelength    | λ      | 1064  | nm   |
| Nominal average power | Pa | 30 | W |
| Pulse frequency | f      | 30 + 80 | kHz |
| Pulse duration | tp     | 50    | ns   |
| Maximum pulse energy<sup>a</sup> | Pe    | 1     | mJ   |
| Maximum pulse power<sup>b</sup> | Pp    | 20    | kW   |
| Scan speed     | Ss     | 1 + 5000 | mm/s |
| Mode           | TEM   | 00    | –    |
|                | M²    | 1.2 + 1.5 | –    |
| Focused spot diameter<sup>c</sup> | – | ≈ 80 | μm |

<sup>a</sup> at Pm = 30 W and f = 30 kHz;

<sup>b</sup> derived from eq. 2 at: Pm = 30 W, f = 30 kHz and tp = 50 ns;

<sup>c</sup> as declared by the producer for a 160 mm flat field lens.

In this way, it was possible to compare homogeneous data and create a sufficiently robust plan for the analysis. The only limitation is that the pulse power and the scan speed were not directly considered. However, these parameters were implicitly taken into account by the frequency (see Eqs. (2) and (3)) and linear energy parameters. In addition, the adopted parameters selection has allowed investigating the process behaviour in a wide range of laser parameters (see Fig. 1). On the contrary, other choices (for example the use of peak power instead of the frequency or of the scan speed instead of the linear energy) would have led to the reduction of the operative window. In Table 3 the experimental plan is summarised; while in Fig. 2 an image of Inconel 718 sheet after laser marking is reported. 5 replications were performed for each process condition.

In order to investigate the geometrical features of the marks, a 3D Surface Profiling System (Talysurf CLI2000 from Taylor Hobson), equipped with an inductive gauge 2 μm radius diamond stylus was adopted. The measurements were performed along the direction perpendicular to the laser scan direction, using a 0.5 μm resolution along the measuring direction and 40 nm in the vertical direction. TalyMap Universal surface analysis software was adopted for the analysis of the geometrical features. In detail, the width, height, depth and total height were acquired. Fig. 3 shows the geometrical features for a certain profile. In addition, after the contrast measurements, cross sections of some marks were metallographically prepared up to 1 μm diamond paste, chemically etched, and observed by optical microscope and SEM.

![Fig. 2. Image of Inconel 718 sheet after laser marking.](image)

Although there are several criteria for marking acceptance/rejection (such as mark geometry, heat-affected zone extension, micro-crack presence, durability under harsh operating conditions) mark contrast is the most important characteristic to qualify the marks, in term of readability. For example, the reading quality of a DM code of aerospace parts can be evaluated through Symbol Contrast and print growth (the extent of dark or light markings) [31]. However, in order to ensure readability effectiveness of the code for all applications, the key issue is contrast: there must be sufficient difference in contrast between the background and the symbol [24].

Several standards regulate mark and code characteristics. As far as the QR code is concerned, ISO 15415 assumes that the image is in high contrast.

In [32], in order to evaluate the contrast in laser marking operation on metals (stainless steel and aluminium alloy) and polymers (polybutylene terephthalate), the authors suggest the use of a spectrophotometer with three different illumination modes (tungsten lamp, daylight, and fluorescent lamp). They found that readability is critically affected by the illumination mode. Moreover, in [33] the same authors found that high analysis sensitivity was obtained under both scotopic (low illumination) and photopic (normal illumination) analysis. Unfortunately, both the methods proposed in [32,33] require sophisticated equipments. A simpler methodology for mark contrast assessment, based on the analysis of images acquired in grey scale with a CCD camera, was proposed in [20] and successfully adopted in [3]. In details, these authors suggest...
Table 3
Adopted process parameters.

| Pa (W) | f [kHz] |
|--------|---------|
|        | 30      | 35  | 40  | 45  | 50  | 55  | 60  | 65  | 70  | 75  | 80  |
|        | Pe (mJ) | 1.00 | 0.86 | 0.75 | 0.67 | 0.60 | 0.55 | 0.50 | 0.46 | 0.43 | 0.40 | 0.38 |
|        | Pp (kW) | 20.0 | 17.1 | 15.0 | 13.3 | 12.0 | 10.9 | 10.0 | 9.2  | 8.6  | 8.0  | 7.5  |
|        | Pe (mJ) | 0.75 | 0.64 | 0.56 | 0.50 | 0.45 | 0.41 | 0.38 | 0.35 | 0.32 | 0.30 | 0.28 |
|        | Pp (kW) | 15.0 | 12.9 | 11.3 | 10.0 | 9.0  | 8.2  | 7.5  | 6.9  | 6.4  | 6.0  | 5.6  |
|        | Pe (mJ) | 0.50 | 0.43 | 0.38 | 0.33 | 0.30 | 0.27 | 0.25 | 0.23 | 0.21 | 0.20 | 0.19 |
|        | Pp (kW) | 10.0 | 8.6  | 7.5  | 6.7  | 6.0  | 5.5  | 5.0  | 4.6  | 4.3  | 4.0  | 3.8  |

Le [J/mm] | 0.60 | 0.30 | 0.20 | 0.12 | 0.06 | 0.04 | 0.03
Ss at Pa = 30 W [mm/s] | 50 | 100 | 150 | 250 | 500 | 750 | 1000
Ss at Pa = 22.5 W [mm/s] | 38 | 75 | 113 | 188 | 375 | 563 | 750
Ss at Pa = 15 W [mm/s] | 25 | 50 | 75 | 125 | 250 | 375 | 500

Fig. 3. Profile features used to qualify a mark: (a) width of the mark (Width); (b) height of the peaks (Height); (c) depth of the groove (Depth); (d) total height (T. Height).

the use of the contrast index, C, calculated as:

\[ C = 1 - \frac{L_{bg}}{L_{fg}} \]

(4)

where \( L_{bg} \) is the background luminance (i.e. the average grey value of the virgin surface) and \( L_{fg} \) is the foreground luminance (i.e. the average grey value of the marked area). According to Eq. (4), a better mark visibility corresponds to a higher C value.

The contrast index C, also known as Weber contrast, is commonly used for achromatic images in cases where small features are present on a large uniform background, or where the background luminance \( L_{bg} \) is higher than the foreground luminance \( L_{fg} \) [34]. These conditions are closer to the ones occurring during the reading of a mark or a QR code on metals, which are usually read in daylight and by means of a camera. Consequently, in the present work, in order to qualify the marking operation (i.e. the mark readability) Weber contrast, hereinafter simply called Contrast (C), has been adopted.

First, mark images were obtained by means of an optical microscope (Zeiss Axioscope 4) in reflected light at 200× magnification and acquired by a digital camera (Nikon Coolpix 4500 mounted on the microscope, at 2272 × 1704 pixels resolution), fixing both the illumination conditions (halogen source with a 90° incident light) and the camera parameters (\( f = 1/60 \) s, \( f = 5.5 \)). The images were compressed at 200 × 150 pixels 256 grey scale image adopting an image processing software and, then, converted into a 200 × 150 ASCII code matrix (0 = black; 255 = white) by way of a custom software developed in MATLAB® environment. The observation area was segmented to evaluate the groove (foreground) and the un-machined (background) zones; 30 × 150 pixel areas were cropped from the groove and from the un-machined areas and the average grey values were calculated for both the areas. Finally,
the Contrast was calculated according to Eq. (4) adopting the averages grey values. Only one measurement for each process condition was performed. In Fig. 4 the schematic of the image elaboration is reported. Then, the experimental data were analysed by ANalysis of VAriance (ANoVA); Response Surface Method (RSM) was adopted in order to develop a forecasting model; in addition, Master Response Optimisation (MRO) was adopted to individuate the optimal process conditions.

3. Results and discussion
3.1. Groove profile geometry

Fig. 5 depicts the profile shapes of three marks obtained by fixing the average power (Pa = 15 W), the scan speed (Ss = 50 mm/s) and changing the pulse frequency (i.e. the pulse power). Besides, they summarise the profiles observed during the investigation. Generally speaking, the analysis of the mark profiles and sections have pointed out the presence of three shape types:

a) marks where all the profile points are positive (z > 0) and/or the mark groove is closed or partially closed, as visible in Fig. 5a, for a mark produced at f = 35 kHz (Pp = 8.6 kW).

b) Gaussian-like mark sections, with an elevated rim (positive peak z > 0 and a negative valley z < 0), as shown in Fig. 5b, for a mark produced at f = 55 kHz (Pp = 5.5 kW);

c) marks where the profiles are quasi flat, like that in Fig. 5c. However, these profiles in the appropriate scale appear as Gaussians-like ones.

Obviously, the mark shape strongly depends on the process parameters. As a matter of fact, type a) marks are mainly obtained for high values of Le (Le = 0.3 – 0.36 J/mm) and low pulse frequencies (30–50 kHz), conditions in which pulse power and pulse energy are maximum.

Some authors affirm that the quality of a mark can be evaluated by considering the depth, the width and the contrast of a mark [20]. Consequently, the relation existing between mark geometrical characteristics and the process parameters, as well as the interaction phenomenas, become a fundamental issue. Fig. 5 shows that, under the same average power (P = 30 W) and scanning speed (v = 50 mm/s), the shape of the cross section changes with the frequency (i.e. the pulse energy). This may be explained by assuming a shift from a keyhole mechanism (low frequency and high pulse energy values) to a conduction mechanism (high frequency and low pulse energy values).

Wlodarczyk et al. [35,36] have studied the effect of pulse energy and number of pulses during the laser marking on different metals (included Inconel 625 and Inconel 718) by way of a 10W Q-switched UV nanosecond laser. The marks were obtained by delivering a pre-defined number of laser pulses (one or more) onto a fixed target, varying the pulse en-
energy in the range 1–5 μJ. They found that there are two critical values for the pulse energy. The first one was called onset value; the second one is, here, called threshold energy. Above the onset energy (1.6 an 1.4 μJ for Inconel 625 and Inconel 718, respectively), the laser-induced surface deformations (LISD) is generated. In this condition the mark appears with a molten and a re-solidified zone, characterised by the typical W-shape and a by a low value of removed material (depth less than hundred nm). Increasing the pulse energy, beyond the threshold values (about 4.4 μJ for both Inconel alloys), the mechanism appears like the ‘keyhole’ one: the craters appear Gaussian-like, with an elevated rim and a high depth. Further increasing the pulse energy, the mark depth and the burr height increase. However, this increase stops when the pulse energy becomes too high, because the molten materials and the groove depth are so high that the vapour pressure is not sufficient to expel the molten material. So, at the end of the laser pulse, the molten material partially collapses inside the hole, causing the filling of the groove and, sometimes, an asymmetric mark growth. In addition, by increasing the number of pulses a slow increase of the depth was observed.

In the present study, although there are similarities with the aforementioned studies [35,36], the operation of the laser in a scanning instead of steady mode, the use of a different wavelength (1070 nm instead of 355 nm) and the use of different energy values (0.19–1 mJ on a beam diameter at focusing point of 80 μm, instead of 1–5 μJ on 11 μm) caused difference in the interaction mechanisms. More in detail, at high Le values (0.6 J/mm), the depth rapidly drops for increasing pulse energy after a Pe > 0.28 mJ (or equivalently a pulse power > 8 kW), in agreement to what observed by Wlodarczyk et al. On the contrary, for low linear energy values (Le = 0.12–0.6 J/mm), the depth increases by increasing the Pe (Le = 0.12 J/mm) or remains almost constant (Le = 0.06 J/mm), as visible in Fig. 6.

To explain the aforementioned results, it must be considered that: the adopted laser is able to release pulses with a pulse power in the range 3.8–20 kW on a beam spot of about 80 μm in diameter. This corresponds to power densities in the order of 10^7–10^8 W/cm^2. According to [37], under these conditions the energy absorbed by the material is high enough to trig the keyhole formation: the material melts and increases its temperature up to vaporisation. The vapour pressure blows the molten material out of the mark groove towards the surrounding area. However, the energy released for single pulse is too low (in the range 0.2–1 mJ) to obtain deep penetration in a single pulse. Thus, the typical Gaussian-like marks, characterized by elevated rim, are generated. Conversely, at low scan speed (i.e. high linear energy), the continuous action of subsequent pulses on the same area increases the absorbed energy and, as a consequence, the material temperature. Thus, the beam penetration enhances up to several hundred microns, in agreement to what observed in [4]. On the other side, the higher is the penetration, the greater the difficulty by the vapors to eject the liquid phase. The latter solidifies at the top and on the edge of the groove giving rise to the a) shape marks.

Also, the appearance of the upper surface of the groove changes by changing the working parameters, in particular with the variation of the pulse frequency, as visible in Fig. 7. The visible side and the cross section of some marks obtained with the same Pa (30 W) and Ss (150 mm/s) values and different pulse frequencies (i.e. pulse power) are reported. From the figure, at \(f = 30\ \text{kHz}\) (\(Pp = 20\ \text{kW}\)), the surface of the mark has a step-like appearance, while at \(f = 80\ \text{kHz}\) (\(Pp = 7.5\ \text{kW}\)), the surface appears smoother and continuous.

It is worth noting that, since the effectiveness of a mark is connected to its readability, the light diffraction and the reflectivity of the mark itself should not be neglected. New surface deformations, such as bumps, dimples, corrugations and ripples, are also generated during the re-melting and re-solidification processes. The appearance of such surface deformations depends on the absorbed laser intensity, on the surface temperature gradients and on the chemical composition of the material [25].

It can be concluded that the mechanisms involved in the mark formation, as well as the contrast, are more complex than those suggested in [35–36] and a higher number of parameters must be taken into account, as also suggested by several authors [19–21]. So, in order to analyse the effect of the process parameters on the mark geometrical characteristics, statistical analysis (ANOVA and RSM) was performed. Moreover, according to the suggestion in [25], it was decided to consider unacceptable those marks in which all the profile points are positive. Then, it was decided to eliminate from the analysis all the data obtained at low Le (0.6 J/mm), since in the latter case, more than 50% of the profiles were of the a) type.

3.2. Statistical analysis of mark characteristics

The purpose of Analysis of Variance is to test for significant differences between means of a response variable (the mark characteristics) by partitioning its total variation into different sources and to compare the variance due to the between-groups (or treatments) variability with that due to the within-group (treatment) variability [38]. Then, a parameter is significant if the change of its level produces a change in the response variable, while an interaction is significant if the response between two levels of one factor depends on the levels of the other factors. The analysis was performed adopting a confidence level of 95% (\(a = 0.05\)). Thus, a control factor or an interaction was significant if the p-value is less than 0.05. The ANOVA assumes that the observations are normally and independently distributed with the same variance for each treatment or factor level. Then, in order to check the normality assumption, diagnostic test on data residuals was performed before the analysis, according to what reported in [38,39]. The results of analysis showed that, except for the depth, the variables not reveal any model inadequacy or unusual problem with the assumptions; consequently, for the Width, the Height, the T. Height and the Contrast, it was possible to assume that the initial assumptions were satisfied. On the contrary, the depth showed a saddle behaviour of the normal distribution; probably it is due to the fact that the measured depth, due to the two different interaction mechanisms observed (conduction and key hole) and despite the discharge of all the data obtained at Le = 0.6 J/mm, remains an uncertain measure (i.e. the measuring method of the depth is unreliable). So, it was decided to neglect the depth. In Table 4 the ANOVA results are summarised in term of F-Value (it is a weight of the effects) and p-value. From the table, on the basis of the adopted assumptions, all the control factors are significant for all the geometrical response variables (i.e. p-value < 0.05). The only exception is the interaction between \(Pp\) Le in the case of the Contrast, that results not significant (p-value = 0.701).

It is worth to note that, due to the limited amount of the data available for the analysis of the Contrast (one replication for each process
setting), the statistical model shows some limitations: the 3 way interaction is not available (for the other response parameters it was expressly discharged by the statistical analysis); moreover, the Contrast shows the worst value in term of R-sq(adj). However, the latter is sufficiently high to be considering the analysis satisfactory.

In addition, for all the mark characteristics, the F-values indicate that the linear energy and the average power are the most influential parameters.

To obtain information about the “effect” of the process parameters, the main effect plots and the two-factor interaction plots were reported in Fig. 8 and Fig. 9, respectively. In the two-factor interaction diagrams the data pertinent to the odd frequency were eliminated for sake of clearness (however, they were taken into account in the ANOVA).

The main effect plots clearly show the effect of the process parameters: all the geometrical characteristics increase in dimension at the increase of either the average power or the linear energy, and decrease at the increase of the pulse frequency (i.e. at the pulse energy increase).

Again, from the Fig. 8a, a linear relationship between the width and the average power seems to be present. Whereas, in all the other cases, this relationship is non-linear. Furthermore, a change in the slope occurs for both the width and the total height when the linear energy overcomes the 0.2 J/mm value. This is a clear symptom of the incoming transition from conductive regime to that of deep keyhole.

The analysis of interaction plots, Fig. 9, shows that the width is more sensitive to a variation of f (or Le) when a low value of Le (high value of f) is adopted and vice versa (Fig. 9a). Conversely, the Height and the T. Height are more sensible to a variation of f (or Le) when a high value of Le (low value of f) is adopted (Fig. 9b and c). About the interactions between the average power and other process parameters (Le and f), Fig. 9 shows that there is a slight different behaviour between the data obtained at Pa = 15 W to the other ones (Pa = 22.5 or 30 W).

About the Contrast, it follows the same behaviours of the geometrical features, except for the f’ Pa interaction (Fig. 9d), that is not statistically significant.

In order to provide a model to describe the relation between the process parameters and the mark geometry, the Response Surface Method (RSM) was adopted. RSM allows obtaining regression models and the corresponding surface plots, to estimate mark characteristics, given a defined set of process parameters. It is worth noting that RSM is a useful instrument for smaller data sets, because it allows obtaining a model with a limited number of tests. However, the adoption of a large number of data does not affect the effectiveness of the instrument.

The regression model provided by RSM consists of an equation that relates the process variables (Pa, f and Le) and their products (Pa², f², Le², Pa × f, Pa × Le and f × Le) to the response variables (Width, Height, T. Height and Contrast) by way of 10 constants (K₁, K₂, ..., K₁₀). The basic formulation of this equation is the following:

\[
\text{Source} = K₁ + K₂ Pa + K₃ f + K₄ Le + K₅ Pa² + K₆ f² + K₇ Le² + K₈ Pa × f + K₉ Pa × Le + K₁₀ f × Le
\]

(5)

where the term “Source” indicate the response variable. Generally speaking, not all the process variables or their products are influent in the models. Then, when this happens, the term Kᵢ of the not significant term can be deleted (Kᵢ = 0) and the variable discharged from the model. Before the model application, the analysis of the statistical significance of the model terms (similar to the ANOVA, but performed on the model) and the error made by the models in the response variables estimation were performed (i.e. R-sq pred.). The results are reported in Table 5. From the table, in the case of the geometrical features, all the terms are significant, so it was not possible to simplify the models. Conversely, for the Contrast, the term f × f, Pa × Le and f × Le are not significant; then, the correspondent terms were discharged from the model.

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**Fig. 7.** SEM images of the upper surface and of a cross section of the marks obtained at Le = 0.2 J/mm (Pa = 30 W; St = 150 mm/s) with different frequency values. The dashed line indicates the separation between the recast and unmolten area.

**Table 4**

ANOVA results for Width, Height, T. Height and Contrast.

| Source       | Width [μm] F-value | p-value | Height [μm] F-value | p-value | T. Height [μm] F-value | p-value | Contrast F-value | p-value |
|--------------|-------------------|---------|-------------------|---------|------------------------|---------|-----------------|---------|
| Pa [W]       | 4304.73           | 0.000   | 967.95            | 0.000   | 1047.54                | 0.000   | 157.95          | 0.000   |
| f [kHz]      | 666.49            | 0.000   | 427.14            | 0.000   | 315.11                 | 0.000   | 31.81           | 0.000   |
| Le [J/mm]    | 3697.00           | 0.000   | 1303.46           | 0.000   | 1293.46                | 0.000   | 164.17          | 0.000   |
| Pa × f       | 11.91             | 0.000   | 9.75              | 0.000   | 8.97                   | 0.000   | 11.07           | 0.000   |
| Pa × Le      | 35.47             | 0.000   | 73.81             | 0.000   | 82.79                  | 0.000   | 3.52            | 0.000   |
| f² Le        | 17.29             | 0.000   | 58.73             | 0.000   | 41.32                  | 0.000   | 0.87            | 0.701   |
| R-sq         | 97.53%            | 0.947%  | 94.31%            | 0.947%  | 93.64%                 | 0.947%  | 88.75%          | 0.000   |
In all cases good value in term of R-sq(pred) was found. Therefore, the models are sufficiently adequate to estimate the mark characteristics. In Table 6 the coefficients of the Eq. (5) are reported. In the Figs. 10–12 the surface plots of the models are reported for $P_a = 30$ W, 22.5 W and 15 W, respectively. Comparing the figures, the geometrical features show a similar trend at the change of $f$ and $L_e$, with their values decreasing as the average power decreases.

Conversely, the Contrast shows a different behaviour, since at the $P_a$ decrease, the response surface tends to decrease more rapidly for high values of $f$ or low values of $L_e$, as visible by comparing Figs. 10d and
Table 5
RSM Table for Width, Height, T. Height and Contrast.

| Source       | Width [μm] | Height [μm] | T. Height [μm] | Contrast |
|--------------|------------|-------------|----------------|----------|
| Pa [W]       | 23.61%     | 10.09%      | 12.23%         | 9.69%    |
| f [kHz]      | 17.24%     | 22.71%      | 19.54%         | 13.00%   |
| Le [J/mm]    | 47.50%     | 36.82%      | 37.95%         | 36.87%   |
| Pa × Pa      | 0.14%      | 0.87%       | 0.93%          | 0.16%    |
| f × Le       | 1.17%      | 1.29%       | 0.22%          | 0.15%    |
| Le × Le      | 3.73%      | 0.63%       | 3.32%          | 8.75%    |
| Pa × f       | 0.30%      | 0.10%       | 0.37%          | 10.65%   |
| Pa × Le      | 0.54%      | 2.64%       | 3.10%          | 0.00%    |
| f × Le       | 1.18%      | 14.73%      | 11.15%         | 0.00%    |

R-sq | 95.40% | 89.89% | 88.82% | 79.33%
R-sq(adj) | 95.36% | 89.79% | 88.72% | 78.26%
R-sq(pred) | 95.29% | 89.61% | 88.53% | 76.31%

* not significant

Table 6
Coefficients of Eq. (5) (Uncoded units).

| Coefficient | Source | Width [μm] | Height [μm] | T. Height [μm] | Contrast |
|-------------|--------|------------|-------------|----------------|----------|
| $K_1$       | Pa [W] | 82.33      | −1.31       | −7.77          | 0.494    |
| $K_2$       | f [kHz]| −0.0371    | −0.02525    | −0.03724       | −0.002452|
| $K_3$       | Le [J/mm]| 352.4      | 124.94      | 204.11         | 3.069    |
| $K_4$       | Pa × Pa| −0.01334   | 0.002196    | n.s.           | n.s.     |
| $K_5$       | f × f  | 0.011664   | 0.003978    | n.s.           | n.s.     |
| $K_6$       | Le × Le| −654.1     | −79.7       | −264.3         | −6.783   |
| $K_7$       | Pa × f | −0.01334   | 0.002103    | 0.00626        | 0.000575 |
| $K_8$       | Pa × Le| −2.938     | 1.979       | 3.062          | n.s.     |
| $K_9$       | f × Le | 1.676      | −1.7986     | −2.2317        | n.s.     |

n.s. = not significant.

11d with Fig. 12d.

3.3. Process optimisation

As aforementioned, the criteria for marking acceptation involve many factors, such as: mark geometry, HAZ extension, the contrast and the process time [3]. However, from the previous paragraph, it can be concluded that all process parameters concur in a different and complex manner to mark geometry and contrast definition. Consequently, the process optimisation should take into account all these parameters at the same time. In order to optimise the process conditions, the Master Response Optimisation (MRO) procedure, proposed by Kros and Mastrangelo in [40] and successfully applied in [41,42], was adopted. MRO method adopts the equations obtained by RSM and finds combinations of input variables (i.e. process conditions) that satisfy the desired targets (i.e. the desired values in term of geometrical features and/or Contrast). To this end, the individual desirability function (di) and constraints must be defined for each mark features. Individual desirability (di) evaluates how the settings optimize a single response, while the constraints are the target and the weight of each mark features (Yi), involved in the optimization. The target is the value to be obtained (minimum, maximum or fixed value). The weight measures the priority in the achievement of the values, by assigning a number in a [0,1] range, where 1 is most desirable value and 0 is not desired one. It determines the shape of the desirability function. Then, if a weight = 1 is assigned for a given features, in the optimum identification, the software will tend to privilege the target assigned for this feature respect to the satisfaction of the other targets. After that, all the single desirability functions are combined in an overall desirability function $Df$ (the average of all the desirability
function $d_i$) in order to simultaneously optimize all the mark features ($Y_i$). The optimal process condition is obtained when $D_f$ achieves its maximum value. For the overall desirability function $D_f$ optimisation, the multiplicative method proposed in [43] was adopted.

Since one of the issues to be addressed in part marking is the achievement of the lowest surface damage (i.e. mark Height and T. Height) and concurrently of the maximum visibility (i.e. Contrast), the adopted model takes in account the Width, the Height the T. Height and the Contrast.

Then, four different scenarios were considered. For each scenario a run was developed and performed according to the setting reported in Table 7. In the first two runs all the mark characteristics were considered; in particular in Run_1 width and Contrast were maximised, while the Height and the T. Height were minimised. Run 2 differs from Run_1 only for the width that was minimised. These two scenarios correspond to two different conditions: Run_1, thanks to the width maximisation, allows a better visibility of the mark; so, it is ideal for the human vision of the mark. The second, since it minimises the mark width, is ideal for marking small codes (included bar code or data matrix) or to perform marks with many details (for instance a logo).

For Run_3 and Run_4, it was preferred to minimise the damage: the width was discharged by the optimisations; the Contrast was maximised, while both the Height and the T. Height were minimised. Run_3 and Run_4 differ for the fact that in Run_4 the weight of the desirability

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**Fig. 11.** RSM surface plots, obtained at $P_a = 22.5$ W for: (a) Width; (b) Height; (c) T. Height; (d) Contrast.

**Fig. 12.** RSM surface plots, obtained at $P_a = 15$ W for: (a) Width; (b) Height; (c) T. Height; (d) Contrast.
Table 7
Constraints imposed in the different optimisation runs.

| Run | Height | T. Height | Width | Contrast |
|-----|--------|-----------|-------|----------|
| 1   | Minimum, $w = 1$ | Minimum, $w = 1$ | Maximum, $w = 1$ | Maximum, $w = 1$ |
| 2   | Minimum, $w = 1$ | Minimum, $w = 1$ | Minimum, $w = 1$ | Maximum, $w = 1$ |
| 3   | Minimum, $w = 1$ | not considered | Maximum, $w = 1$ | |
| 4   | Minimum, $w = 5$ | Minimum, $w = 1$ | Maximum, $w = 1$ | |

$w =$ weight.

Table 8
Optimisation results in term of process parameters, mark characteristics and desirability.

| Run | Pa [W] | $f$ [kHz] | Le [J/mm] | Width [μm] | Height  [μm] | T. Height [μm] | Contrast | Desirability |
|-----|--------|-----------|-----------|------------|-------------|---------------|----------|--------------|
| 1   | 30     | 80        | 0.3       | 145.37     | 8.09        | 14.00         | 0.55     | 0.79         |
| 2   | 15     | 35        | 0.03      | 97.13      | 2.75        | 4.27          | 0.29     | 0.73         |
| 3   | 25.90  | 80        | 0.5       | –          | 6.03        | 10.42         | 0.46     | 0.79         |
| 4   | 18.78  | 80        | 0.3       | –          | 0.44        | 1.22          | 0.27     | 0.75         |

Fig. 13. Optimization Plot for: (a) Run 1; (b) Run 2; (c) Run 3; (d) Run 4.

function for the Height was set equal to 5. In all the other runs, the weights adopted in the desirability functions were always set equal to 1 (see Table 7). The optimisation results are reported in Table 8 in terms of process conditions, mark characteristics (geometries and Contrast) and overall desirability. The same results are reported in graphical format in Fig. 13. The figure shows, in the frames on the right the optimal process condition identified by the MRO analysis (also indicate by the vertical lines) together with the values in the surroundings of the selected solution. On the left, the values of the resulting mark characteristics and overall desirability for the adopted solution.

From Table 8 (or equivalently Fig. 13), the overall desirability always reaches a sufficiently high value (greater than 0.7 compared to the max-
imum value equal to 1). The width varies from 145.37 µm for the Run_1 (width = maximum) to 97.13 µm for the Run_2 (width = minimum), corresponding to the 80% of the maximum measured value and 150% of the minimum measured value. The Contrast varies in the range 0.55–0.27, depending on the selected Run, corresponding to about 95% and 48% of the maximum measured value (i.e. C = 0.57), respectively. The Height and the T. Height vary in a larger range (0.44–8 µm and 14–1.22 µm, respectively), depending on the adopted constraints. The analysis clearly indicates that the MRO does not permit to satisfy all the requests at the same time, but, it allows finding a compromise between the different requirements. Moreover, it is worth noting that when a high weight is adopted (like in the case of Run_4), the MRO achieves a solution able to promote the specific parameter as compared to the others.

In order to verify the results of MRO, the data of Table 8 were compared with the experimental data in Fig. 14. The figure reports the Contrast against the mark geometrical features (Width, Height and T. Height). In the figure the open dots represent the experimental data; while the full markers the data provided by the MRO procedure. First of all, the solution proposed by the MRO falls on the experimental data. Moreover, from the figure it is possible to see that the Contrast increases at the increasing of all the geometrical features. However, while for the width (Fig. 14a) a high data scattering is observable, for the other two features the Contrast steadily increases up to C = 0.55; then it remains about constant, irrespective to the further increases of the geometrical features. The maximum Contrast was achieved at a critical Height or a critical T. Height of about 9 µm and 14 µm, respectively (the vertical dashed line in Fig. 14b and c). Then, Fig. 14 explains why the MRO does not allow to satisfy all the requests at the same time: there is no process condition able to give the maximum Contrast and minimum geometric features. On the other hand, Fig. 14 shows the ability of MRO to find a compromise between the different requirements. As matter of fact, for Run_1 and Run_2, the MRO found a solution really able to give high and low values of width, respectively, without sacrificing the other constraints excessively (including the Contrast). A similar comment is also valid for Run_3, where the proposed solution falls into the area beyond which an increase in Height (or T. Height) does not lead to a noticeable increase in Contrast. Of particular interest is the result of Run_4, which points fall into an area that, despite the low values of the Height (and the T. Height), still has a good Contrast values.

4. Conclusion

Laser marking tests were performed on inconel 718 alloy sheets, 1 mm in thickness, by adopting a 30 W Q-switched Yb:YAG fiber laser, in order to study the influence of the process parameters on the mark geometry and readability (Weber contrast). Statistical methodology was adopted in order to analyse the effect of the process parameters, provide an analytical model of the process and optimise the process conditions. From the results, within the experimental conditions adopted in this work, the main conclusions are the following.

- The marking formation involves all the analysed parameters in a complex way.
- Two types of marking mechanisms have been observed: by conduction and by keyhole. The latter is unwanted since it creates a deep penetration and high burr height.
- The average power (P_a) and the linear energy (L_e) play a fundamental role in the mark geometry formation: all the geometrical features increase at the increase of P_a and L_e.
- Pulse frequency also has its weight in the formation of the mark geometry. In particular the decrease of the frequency, since it involves an increase of the pulse power (or equivalently the pulse energy), triggers the keyhole phenomenon.
- The Contrast is strictly related to the process parameters as well as to the mark geometry.
- The Contrast linearly increases at the increase of both the burr height and the total height up to a value C = 0.55; then it remains almost constant, irrespective of the further increase of the geometrical features. Consequently, it is not recommended to overcome a Height or a T. Height higher than 8 and 14 µm, respectively.
• Response Surface Method (RSM) provides statistical models able to describe the geometry and the Contrast behaviours as a function of the process parameters.

• The Master Response Optimization (MRO) does not allow finding an ideal solution, as the latter, simply, does not exist. However, once the constraints are properly set, MRO is effective in identifying valid compromise solutions.

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