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# EVALUATION METHODS FOR CARBON STEEL LASER CLEANING PROCESS

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**Abstract.** *Cleaning materials through laser processing has been increasingly used since it is fast, sustainable, and simple when compared to other competing processes. A great utility of laser cleaning is related to the removal of corrosion layers from metallic surfaces. Through the burning reaction of the laser against the surface oxide, corrosion can be removed, making clean and ready for use an oxidized and unsuitable metallic part surface. The main obstacle in the case of laser cleaning parametrization is to find a correct set of parameters such as laser power, pulse frequency, and laser speed that are suitable for each material, and to define cleaning quality criteria. Thus, in this work, a cleaning experiment is presented, aiming to reflect a common case in the industry: to define cleaning parameters for a carbon steel plate taken by atmospheric corrosion. The experiment consisted of applying radiation from the laser on the steel plate with the corroded surface. Some preliminary tests were carried out trying to find the range of parameters that demonstrated different degrees of cleanliness. Cleaning was carried out in small square-shaped regions, with 5 mm sides. In each square, different power and frequency settings were combined, resulting in a matrix with 12 squares. From the established parameters, the results obtained were analyzed both by a computer vision system, which generated contrast values in relation to the plate without cleaning, and by a Scanning Electron Microscope, in which a deeper visual analysis could be done and, a preliminary chemical analysis. Through microscopic analysis, it was realized that the vision system evaluation results were not completely reliable but helped to better understand the cleaning phenomenon. Since the parameters with less power and higher frequency are less aggressive to the sample, and apparently do not alter the microstructure of the base material, they showed to be more appropriate for this task.*

**Keywords:** *Laser Cleaning, Corrosion, Computer Vision System.*

## 1. INTRODUCTION

Surface cleanliness of engineering materials is of great interest in both engineering and scientific fields. It is known that the surface cleanliness of metals affects their workability, mechanical life, and reliability as well as the resistance to corrosion and rust (Chen *et al.*, 2012). Corrosion related problems are frequent and occur in many different areas, such as the chemical, oil, shipbuilding, and automobile industries, in air, rail, subway, maritime, and road transport, and in communication media such as telecommunications systems, in dentistry (metal restorations, prosthetic devices), in medicine (orthopedics), and in artworks such as monuments (Zhang *et al.*, 2018). For corrosion control, most methods consist of interposing a protective layer between the metal and the corrosive medium. These protective layers can be formed naturally or artificially, and in some cases simultaneously (Gentil, 1996).

Often, the desired goal is to prepare a surface for a later procedure, such as painting. For this, it is desirable to have a minimum of corrosion on the surface, facilitating the adhesion of the paint. This type of cleaning can be done by laser (Sobotova *et al.*, 2020).

Over the years there has been an increased interest in the use of laser radiation for surface cleaning. The technique offers significant advantages when compared to other competing methods, such as: localized treatment, remote application (some distance from the part/surface), which greatly facilitates the cleaning of parts with complex geometry (Psyllaki and Oltra, 2000; Sobotova *et al.*, 2020; Zhang *et al.*, 2018; Poprawe, 2011).

Laser cleaning offers a new range of opportunities and processing techniques for surface layer removal that can overcome the limitations of current processes. In recent years, in addition to conventional cleaning techniques (chemical, thermal, and mechanical), laser cleaning has become increasingly important (Guo *et al.*, 2019). The reasons are the advantages in engineering processes (no contact, no defects, high precision, low heat influence on the base material), as well as the ability to meet the strictness of legislation, as it is currently concerned with hygiene issues and reducing waste and pollution (Poprawe, 2011).

Thus, laser cleaning has grown in importance, particularly in applications such as the removal of small debris

particles in semiconductors and in art conservation (Sobotova *et al.*, 2020). With the introduction of the Montreal Protocol, which, for environmental and public health reasons, proposes long-term reductions in the use of organic solvents such as CFC's, which are also used in industrial cleaning, it is expected that more industrial applications of laser cleaning will emerge in the coming years (Steen and Mazumder, 2010).

## 2. LASER CLEANING

Within laser processes, cleaning is characterized as an ablation process, i.e., the removal of material from a surface by means of vaporization (Li *et al.*, 2021; Poprawe, 2011). Cleaning is based on the locally confined, non-contact interaction of continuous or pulsed laser radiation with the surface layer (Poprawe, 2011).

There is a range of mechanisms by which radiation can remove material from a surface. They are basically classified into three groups. However, each process below can involve more than one mechanism:

1. Evaporation process - selective vaporization, ablation;
2. Impact processes - scattering, evaporative pressure, photon pressure, dry and vapor cleaning, laser shock cleaning;
3. Vibration processes (based on acoustic or thermoelastic forces) - transient heating, angular laser cleaning (Steen and Mazumder, 2010).

Depending on the composition and thickness of this layer and the process parameters, different cleaning mechanisms can be defined:

1. Ablation by evaporation or decomposition (sublimation) of the surface layer;
2. Removal by thermally induced stresses or shock waves induced by the laser beam (Poprawe, 2011);

In technical surface layers, many mechanisms can occur simultaneously. In turn, the dominant mechanism depends on the material properties and the process parameters, mainly laser wavelength, energy density, and interaction time (Qiang *et al.*, 2016).

As shown in Figure 1, if the surface layer (with absorptivity  $A_D$ ) absorbs well the laser radiation of the selected wavelength range, and if the substrate (with absorptivity  $A_G$ ) has a small absorption i.e.,  $A_D > A_G$ , the cleaning process is called "self-limiting". At the beginning of the process, a large amount of incident laser radiation is absorbed and converted into thermal energy. Due to thermal conduction, the base material heats up as the interaction times increase ( $t_2 > t_1$ ). To avoid damage to the base material the interaction time must be short. If the energy density limit for reaching the oxide surface evaporation temperature (represented by  $I_D$ ) is exceeded i.e., applied energy density  $I_L > I_D$ , evaporation of the surface layer occurs. However, there should be not remaining applied energy density to also overcome the substrate evaporation temperature (represented by  $I_G$ ). This way, the process runs better when  $I_D > I_G$ . When the surface layer is completely removed, the laser radiation interacts with the base material and ideally is reflected in a large amount, so the cleaning process is over, and no defects should occur in the base material.

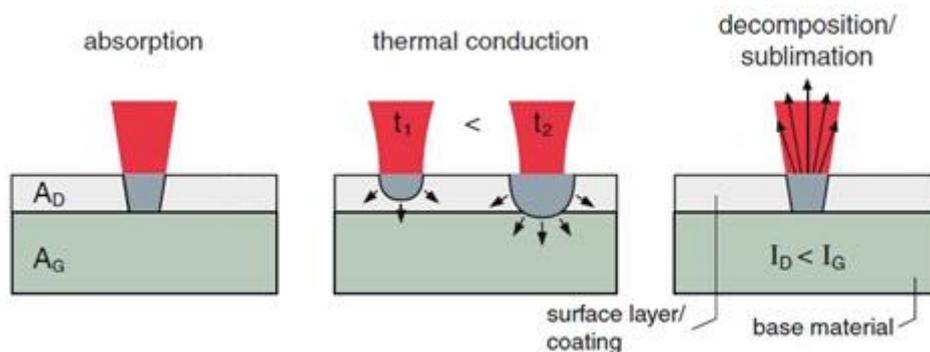


Figure 1. Scheme of the ablation/cleaning process (Poprawe, 2011).

### 2.1 Corrosion

In many applications, the removal of oxides from surfaces is necessary to enhance the function of a metal component. For example, stainless steel surfaces must be cleaned prior to welding because the presence of oxides increases the tendency for the joint to become brittle, and decreases its mechanical strength (Psyllaki and Oltra, 2000).

In a very widespread and universally accepted aspect, corrosion can be defined as the deterioration of a material, usually metallic, by chemical or electrochemical action of the environment combined or not with mechanical stress (Francis and Hebdon, 2019). The deterioration caused by the physical-chemical interaction between the material and its operating environment represents undesirable harmful changes suffered by the material, such as wear, chemical variations, or structural modifications, making it unsuitable for use (Fu *et al.*, 2020). Since corrosion is, in general, a spontaneous process, it is constantly transforming metallic materials so that their durability and performance no longer meet the purposes for which they were intended. This phenomenon assumes transcendental importance in modern life, which cannot do without metals and their alloys (Gentil, 1996).

Corrosion can have direct and indirect consequences, some of which are economic in nature, such as:

1. Replacement of corroded equipment;
2. Equipment downtime due to failures caused by corrosion;
3. Preventive maintenance jobs - painting, adding corrosion inhibitors, coatings;
4. Contamination or product loss.

Corrosion processes are heterogeneous chemical reactions or electrochemical reactions that generally take place on the separation surface between the metal and the corrosive medium (Li *et al.*, 2019). Considering as oxidation-reduction all chemical reactions that consist in giving up or receiving electrons, one can consider the corrosion processes as oxidation reactions of metals, that is, the metal acts as a reducer, giving up electrons that are received by a substance, the oxidizer, existing in the corrosive environment (Song *et al.*, 2021). Therefore, corrosion is a way of destroying metal, progressing through its surface (Gentil, 1996).

### 3. MATERIALS AND METHODS

For the execution of the experimental procedure, a Iterbium fiber laser source from the Max Photonics manufacturer was used. This laser works in pulsed mode with a pulse width of 94 ns, has a maximum power of 50W, and generates a wavelength of 1064nm.

For this experiment fixed and variable parameters were defined. Fixed parameters considered in this experiment are:

1. Pulse Width: It is the time in which a single pulse of the laser beam falls on the sample. In the case of the laser used, it is a fixed parameter, but there are models where this number can be configured within a range of values;
2. Speed: This is the speed at which the beam moves over the sample in the  $x$  and  $y$  axes. This movement is due to the speed of rotation of the galvanometers in the scanner;
3. Fill: The fill parameter explicitly defines the lateral distance between successive pulse emission lines, as shown in Figure 2 (Dutra, 2017).

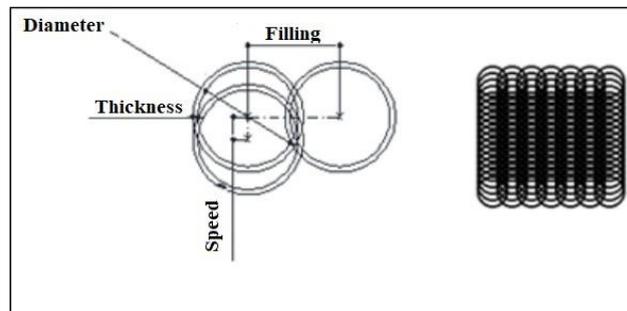


Figure 2. Influence of Filling (Dutra, 2017).

4. Scan angle:  $0$  and  $90^\circ$  - This is the factor that indicates which direction the laser beam will move. For example, at  $0^\circ$  the beam moves to deliver pulses from left to right, horizontally. At  $90^\circ$ , the sweep is from top to bottom, vertically.

Through preliminary tests, and observation of the results, it was established that the parameters to be varied would be the frequency and the output power. These are variable parameters in this experiment:

1. Frequency: Number of pulse repetitions per second. Unlike what you might assume, the pulse width remains fixed even when you change the frequency of the pulses. Changing the frequency results in a variation in the period between pulses, not in the duration of the pulse itself;
2. Laser power: With the possibility of varying the laser output power, different fractions of the total power were worked with, resulting in different pulse energies on the sample.

It was used a low carbon unspecified steel plate, with a completely and uniformly corroded surface. The plate is 1.5 mm thick, and its corrosion occurred naturally, over the time it was stored. As the main idea is to do not modify or damage the substrate its composition determination is not a concern. The experiment consisted in applying the laser radiation specified above on the steel plate with the corroded surface. Some preliminary tests were carried out to find the range of parameters that would demonstrate different degrees of cleanliness. The cleaning was performed in small square-shaped regions, 5 mm on each side. In each square, different power and frequency settings were combined, resulting in a sort of matrix with 12 squares, arranged in the following configuration, as shown in Figure 3:

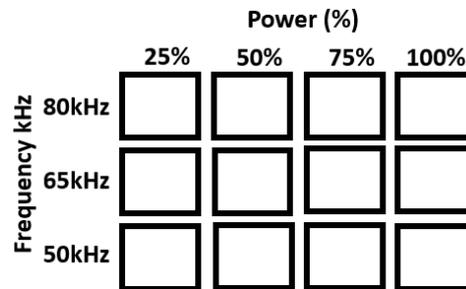


Figure 3. Schematic of the experiment's parameter matrix.

Table 1 shows the established fixed and variable parameters.

Table 1. Parameters set for the Experiment.

Fixed parameters	Values	Unit
Speed	3500	mm/s
Pulse Width	94	ns
Scan angle	0; 90	°
Filling	0, 04	mm
Variable Parameters	Values	Unit
Frequency	80; 65; 50	kHz
Power	12,5; 25; 37,5; 50	Watts

In addition, 6 different arrays were made, where in the first one the laser passed only 1 time over the sample, in the second one 2 times, and so on. The generated patterns were photographed right after the test, and the images obtained were analyzed using a computer vision system, developed by Dutra (2017). The system captures images and transforms them into a black and white scale (global thresholding), measuring the contrast difference between the darkest and the lightest point. In addition to the analysis of the photos, images acquired in real-time were evaluated, as shown in Figure 4.

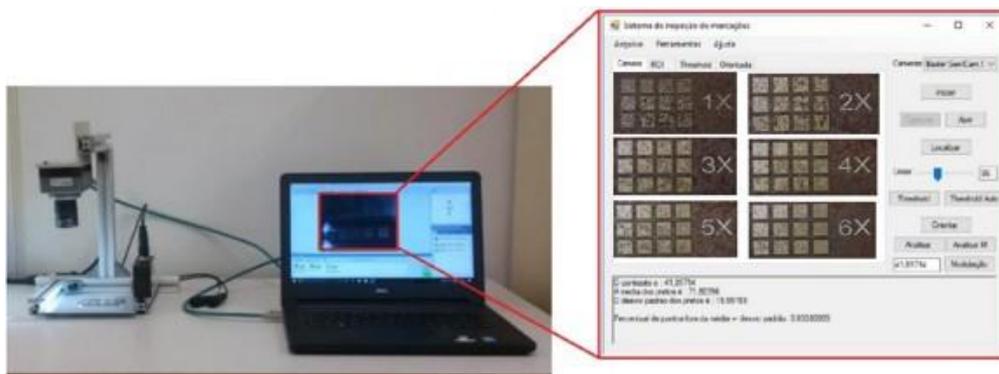


Figure 4. Computer Vision System Hardware and Software view.

#### 4. RESULTS AND DISCUSSION

The processing time for the first array was 0,914 s (one scan at 0° and one at 90°), resulting in an average of 0,076 s for each cleaned square. The second array took twice as long, and so on. Figure 5 shows the pictures of each cleaned matrix as used for analysis in the computer vision system. Each number beside the matrix corresponds to the number of times the laser was scanned.

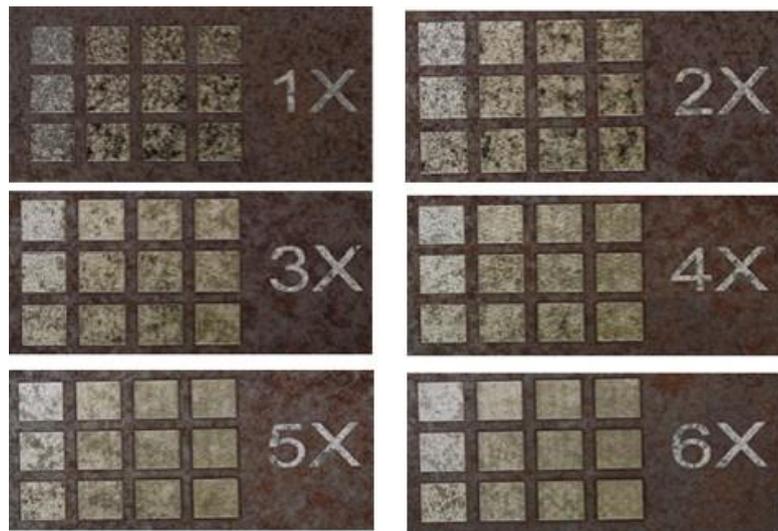


Figure 5. Images of the matrices obtained on the sample.

Table 2 presents the digital image contrast values for each matrix and each square. The squares are identified by row and column indicatives (RxC) for better understanding:

Table 2. Contrast values of each square of the matrices, indicating the position of the squares per row and column.

Matrix	Power (%)								Frequency (kHz)
	25		50		75		100		
	RxC	Contrast	RxC	Contrast	RxC	Contrast	RxC	Contrast	
1	1x1	31,7	1x2	31,2	1x3	30,4	1x4	27,5	80
	2x1	34,4	2x2	35,6	2x3	32,9	2x4	31,0	65
	3x1	33,9	3x2	35,4	3x3	31,0	3x4	28,6	50
2	1x1	58,3	1x2	55,1	1x3	51,6	1x4	45,4	80
	2x1	58,0	2x2	50,8	2x3	50,2	2x4	46,2	65
	3x1	56,6	3x2	52,9	3x3	47,9	3x4	45,8	50
3	1x1	54,5	1x2	51,4	1x3	45,8	1x4	48,7	80
	2x1	52,2	2x2	45,4	2x3	40,6	2x4	42,6	65
	3x1	48,9	3x2	42,4	3x3	40,6	3x4	40,6	50
4	1x1	56,9	1x2	56,3	1x3	53,3	1x4	46,1	80
	2x1	56,2	2x2	48,2	2x3	47,9	2x4	46,4	65
	3x1	53,5	3x2	48,7	3x3	47,1	3x4	46,0	50
5	1x1	53,7	1x2	50,7	1x3	46,0	1x4	44,0	80
	2x1	54,3	2x2	47,0	2x3	43,2	2x4	40,2	65
	3x1	52,3	3x2	44,5	3x3	42,6	3x4	39,0	50
6	1x1	50,6	1x2	47,6	1x3	42,6	1x4	37,9	80
	2x1	47,3	2x2	43,9	2x3	37,4	2x4	34,8	65
	3x1	48,5	3x2	43,0	3x3	40,1	3x4	37,3	50

In Table 3 and Figure 6 one can see the progression of the contrast values on the curve plotted with the results obtained with the 80 kHz frequency, as the configuration that presented the highest contrast values.

Table 3. Contrast values with fixed frequency of 80 kHz.

Matrix	25%	50%	75%	100%	Frequency
1	31,7	31,2	30,4	27,5	80
2	58,3	55,1	51,6	45,4	80
3	54,5	51,4	45,8	48,7	80
4	56,9	56,3	53,3	46,1	80
5	53,7	50,7	46,0	44,0	80
6	50,6	47,6	42,6	37,9	80

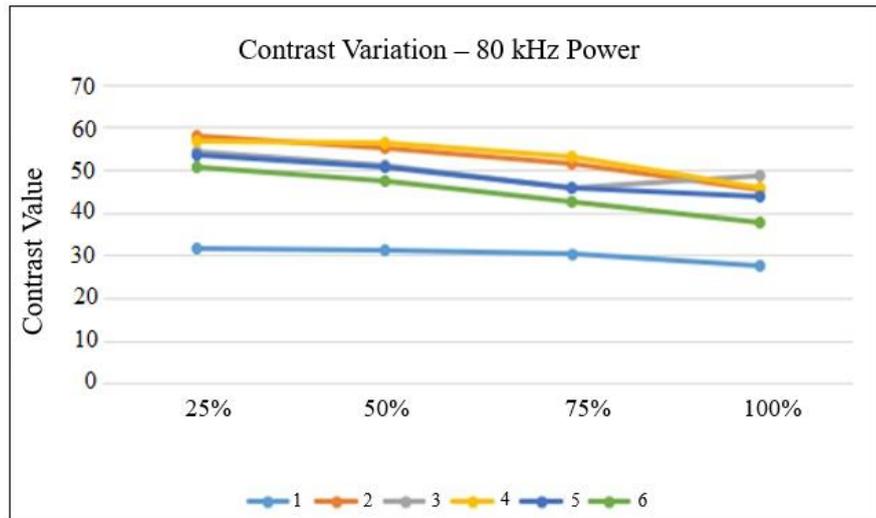


Figure 6. Graphic referring to table 3.

In general, the values show a drop in contrast as the power is increased. As already mentioned, the system also analyzed the sample in real-time. However, due to the low quality of the illumination and the resolution of the camera used, not all squares of the sample were analyzed, only the 1x1 squares of each matrix. The values obtained were compared with the values of the same squares analyzed by the photos. The comparison follows, as show in Figure 7 and 8.

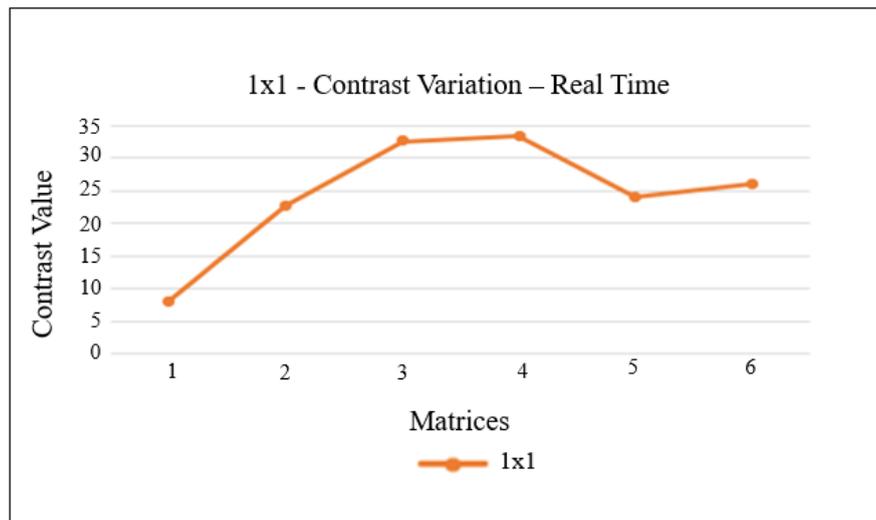


Figure 7. Progression of the contrast values for the 1x1 square of each matrix in the real-time analysis.

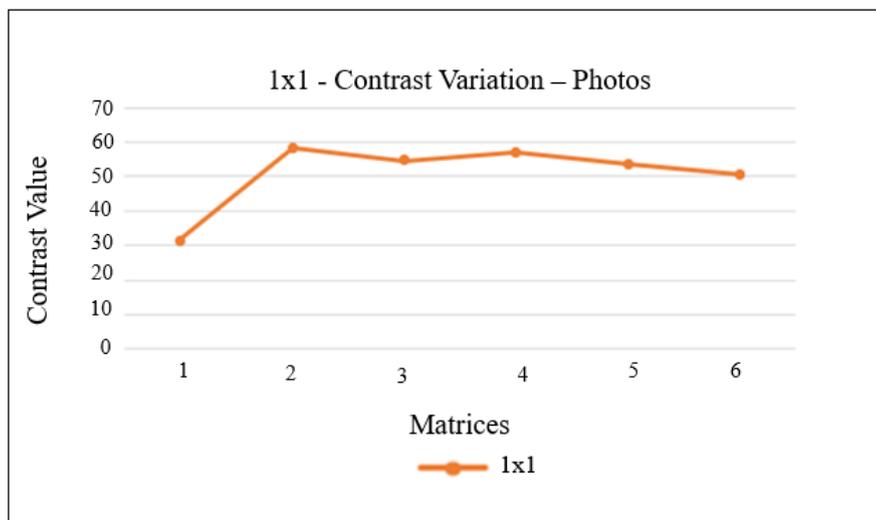


Figure 8. Behavior of the contrast values for the 1x1 square of each matrix in the photo analysis.

It is possible to notice that the behavior was similar because the square of the first matrix presents a smaller contrast value, and the following values have a smaller variation. The difference in values is because the ambient lighting at the time of real-time acquisition was lower than at the time of the photographs, and therefore, did not generate as much contrast between the regions. To generate a comparative result, the same samples were submitted to analysis in the Scanning Electron Microscope, seeking a comparison with the contrast results, through chemical analysis by EDX. In addition to the images used to perform the chemical analysis, other images of the samples were obtained seeking to better demonstrate the effect of the laser on the surface of the samples. For reference purposes, Figure 9 below shows a picture of a region without cleaning, the red arrows highlight the oxide regions.

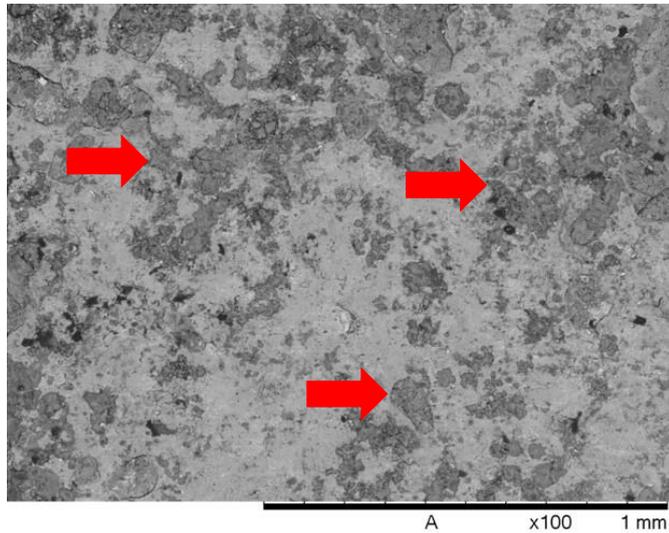


Figure 9. Appearance of the unclean region, containing various oxides.

Figure 10 shows the 1x1 square images of each matrix shown in Figure 5.

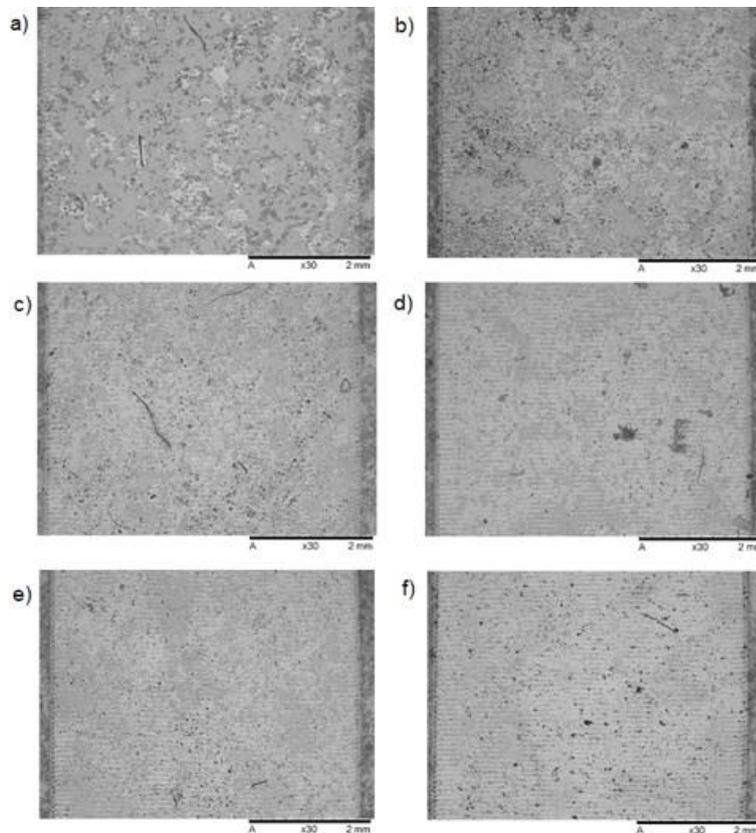


Figure 10. Images of the 1x1 square of all matrices made, at 30x magnification. a) Matrix 1 b) Matrix 2 c) Matrix 3 d) Matrix 4 e) Matrix 5 f) Matrix 6.

As the laser passes more times, more corrosion material is removed as shown in Figure 10. The lighter regions of the images show the metal substrate, but much of the image still consists of the oxide regions, demonstrating that the laser was able to remove only the most superficial layers of oxides. To further investigate the experimental investigations about the parameters influencing the laser cleaning process, some squares of the arrays were chemically analyzed using EDX, where a qualitative (X-ray scattering spectrum) and semi-quantitative overview of what kind of elements were present in the sample and which cleaning parameters were most effective can be obtained. Since the results of the vision system were obtained before this analysis was performed, it was decided to do the analysis in more squares in matrix 2, which showed the highest contrast, and in matrix 6, which visually appeared to have removed more oxides from the surface. Below are the mass percentage values of the three main elements for all the squares analyzed, as shown in Figure 11.

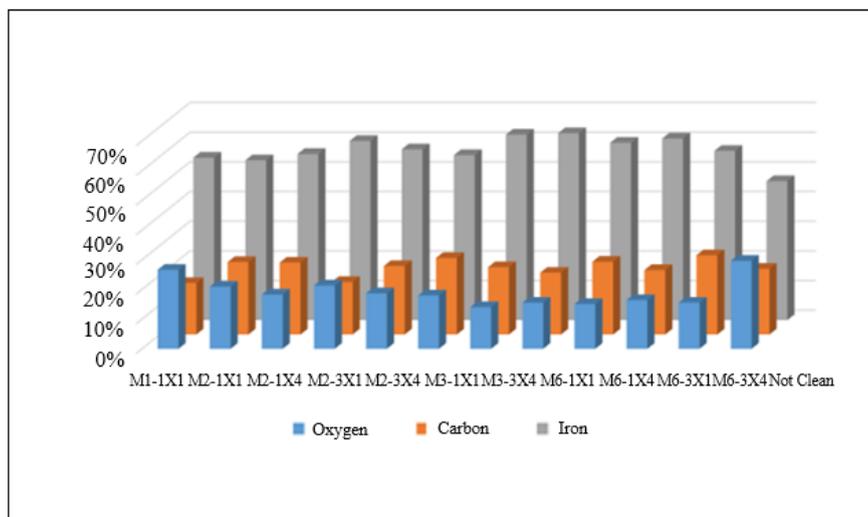


Figure 11. Mass percentage value of the elements iron, carbon and oxygen in all analyzed squares, together with the values of the unclean region.

According to this analysis, the cleaning parameter that removed the most oxygen from the surface was the 3x4 square of matrix 3, with a frequency of 50 kHz and 50 W of power. Another noteworthy parameter is the 1x1 square of matrix 6, with a frequency of 80 kHz and 12.5 W of power, which achieved the highest percentage of iron in the composition.

## 5. CONCLUSIONS

In view of the tests performed, it can be concluded that, despite the many possibilities of laser work and its many parameters, it is possible to find good settings for cleaning. The results obtained reached the goal, to work in the range from insufficient cleaning to "saturation" cleaning. The parameters were based on practical experience and proved to be effective through experimentation. With the analyses performed it cannot be stated that the higher contrast value measured in the vision system results in a better quality of cleaning, but with the images obtained by the SEM, one can better understand the phenomena occurring on the surface of the material, providing a reliable basis for observation of the cleaning. It can be said that the parameters with lower power and higher frequency are less aggressive to the sample, and apparently do not change the microstructure of the parent material so abruptly. In this way the material becomes more reflective to light when its corrosion layer is removed, and this may be the factor that leaves higher contrast values for these parameters, besides, of course, the non-standard conditions of the photographs (distance and position of the sample, camera settings, illumination.). In more aggressive settings, substrate remelting was observed, which altered the surface roughness more significantly, leaving it less reflective, despite containing less oxides.

## 6. ACKNOWLEDGEMENTS

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