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Modeling the Influence of Grain Morphology on the Laser Engraving Processes

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Abstract. **The study describes the Monte Carlo modelling of the ablation depth during the laser marking process. The effect of grain size on the resulting roughness is studied. The results were validated by experiments with model samples of pure iron with different grain sizes. The influence of the laser power, speed and raster distance were also studied and commented.**

Keywords: Engraving, Grains morphology, Laser ablation

I. INTRODUCTION

The pulse fibre laser system are successfully used to engrave metal surfaces for the purpose of creating labels, protection signs, engineering coding. They are also used to prepare different type of micro and mezzo micro fluidic channels for MNT tooling and other type of surface structuring (e.g. for designing specific tribological characteristics) [1]-[3]. In all cases the surface roughness and integrity is of paramount importance.

The surface characteristics (roughness and surface integrity in general) of the laser processed materials depend on the technological parameters such as raster pitch and scanning speed but it is also supposed to depend on [4]-[8] the material morphology - the size of the grains in first place. The last issue is not very well studied and with regards to the particular materials different and controversial results are reported. The grain size of a metallic sample can affect the laser ablation depth through a number of mechanisms [9]-[12]:

- Small grain sizes can lead to reduced thermal conductivity in the material, which can cause the material to heat up more quickly during laser ablation. This can result in increased melting and vaporization of the material, leading to higher ablation depths.

- Absorption of laser energy by a material can be affected by its grain size. In some cases, smaller grain sizes may result in increased absorption of laser energy, which can lead to increased melting and vaporization and therefore deeper ablation.

- If small grain sizes lead to rougher surfaces they can scatter laser energy and reduce the effective energy density at the surface of the material. This can result in an opposite effect - shallower ablation depths.

- Grain size can also affect the mechanical and physical properties of a material (hardness, strength, and ductility). These properties are a function of the internal stresses of 3rd order (stresses that are introduced in the crystal lattice and are balanced out within the crystal grain). These stresses and the corresponding increase of the phase internal energy may influence how the material responds to laser ablation, and can therefore affect the ablation depth.

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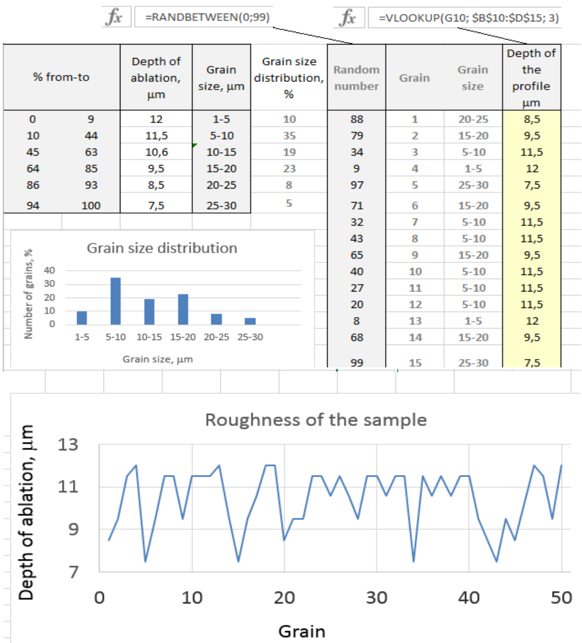
In general the relationship between grain size and laser ablation depth can be complex and depend on many factors, including the specifics of the material, laser parameters, and experimental conditions. Therefore, it's important to characterize the material properties and optimize the laser parameters for each specific case to achieve the desired ablation depth.

The aim of this research is to create a digital model (using the Monte Carlo method) for studying the influence of the grain size morphology on the surface roughness of the sample.

Validation of the model was carried out with a 1064 nm nanosecond fibre laser PL F 20 (10W, pulse duration 30 ns, pulse frequency 20 kHz and spot size 30 µm), raster pitch in the range of 20 to 80 µm and the scanning speed of 75 to 200 mm/s. The conducted experiments analyse the influence of the parameters on the roughness and penetration depth in low carbon iron alloy (0.04%C; 0,12%Si; 0,16%Mn; <0,01%P; <0,01%S; 0,05%Cr; 0,09%Ni; 0,16%Cu). This material was chosen for its nearly single α-Fe phase content and the ease of modelling the grain size structure by applying different heat treatments.

II. MATERIALS AND METHODS

Since the distribution of grains in the material according to their size is statistically determined, but random for a given sample or section, it can be simulated using random numbers generated by a computer program. In EXCEL this could be done using the RANDBETWEEN function. If we have data about grain size distribution and the ablation depth of grains of different sizes then using a tabular model in EXCEL [13] and the VLOOKUP function we can create a link between them (Fig.1). So on each randomly generated grain size we can assign corresponding ablation depth. In this way a model of a profile of the surface of the material is obtained similar to the diagram taken by a contact profilometer or surface roughness tester.



% from	to	Depth of ablation, µm	Grain size, µm	Grain size distribution, %
0	9	12	1-5	10
10	44	11,5	5-10	35
45	63	10,6	10-15	19
64	85	9,5	15-20	23
86	93	8,5	20-25	8
94	100	7,5	25-30	5

Random number	Grain	Grain size	Depth of the profile µm
88	1	20-25	8,5
79	2	15-20	9,5
34	3	5-10	11,5
9	4	1-5	12
97	5	25-30	7,5
71	6	15-20	9,5
32	7	5-10	11,5
43	8	5-10	11,5
65	9	15-20	9,5
40	10	5-10	11,5
27	11	5-10	11,5
20	12	5-10	11,5
8	13	1-5	12
68	14	15-20	9,5
99	15	25-30	7,5

Fig. 1. The model and surface profile of a sample.

For obtaining the data of ablation depth the steel samples were heat treated to produce different and relatively uniform size of the grains [14] [15]. The samples were heated in electrical furnace for 5 hours to 1000 ºC and cooled with different speeds (using hot and cold oil, water, air with and without ventilation, cooling with the furnace, etc.). This way model samples were produced with average grain size from 13 to 37 µm (Fig. 2). This samples were treated with the laser with scan speeds 75, 100, 125, 150, 175, 200 mm/s and the depth of ablation and roughness were measured using LEXT OLS5000 laser microscope. The apparatus allows simultaneous 2D and 3D measurement and observation of the deep-focus field. The microscope works according to ISO/TC 213 and ISO 2517 surface roughness measurement standards.

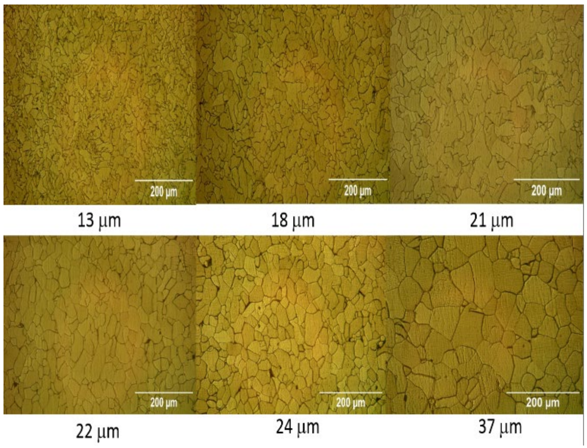


Fig. 2. Grain morphology after the heat treatment.

III. RESULTS AND DISCUSSIONS

The geometrical and technological parameters (Fig. 3) of the laser ablation process (laser beam spot, speed of scanning, step of scanning, grain size) are supposed to be of main importance to the final result - the roughness of the material surface and its exploitation characteristics.

Depending on the purpose of the product, the requirements for roughness are different and often contradictory. In engraving greater roughness can have a positive effect on contrast and resolution but in micro-features production and surface structuring (e.g. for MEMS tooling, microfluidic channels, etc.) - lower roughness improves product quality.

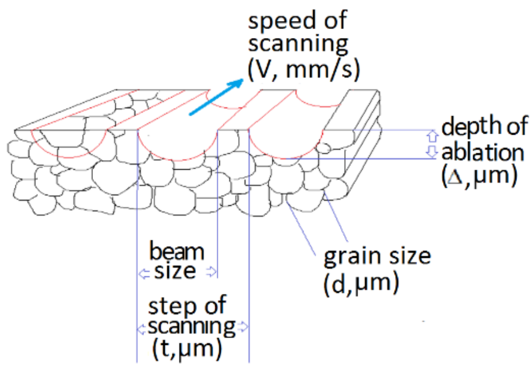


Fig. 3. Parameters of the laser ablation process.

Scanning speed

Decreasing the scan speed leads to an increase in the depth of ablation for all grain size samples and consequently to higher sample roughness. The reason is the increase of the linear density of the applied laser energy. This result illustrates a possible way to achieve better contrast but at the expense of increasing the engraving time. At the same time, as can be seen from Fig. 4 decreasing the scan rate leads to an increase in the influence of the grain size on the depth of the profile (the points of the graph corresponding to low scan rates - e.g. 75 mm/s are tree times more spread out compared to the points corresponding to the 200 mm/s).

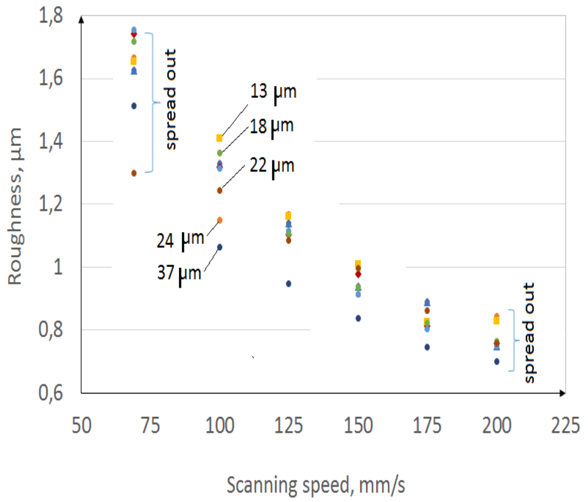


Fig. 4. The influence of the scanning speed on the roughness of the samples.

Scanning step

When the scan step is decreased the surface roughness is decreased (Fig. 5) due to the increase in the surface density of the applied laser energy when the laser beam spots overlap or are close to each other. This means that we will have the effect of flattening the surface profile. This illustrates the way the surface smoothness could be improved but this effect will be at an expense of increase the technological time. If the higher contrast is desirable than the scan step should be increased with caution since the rather sparse lines will affect the contrast of the picture.

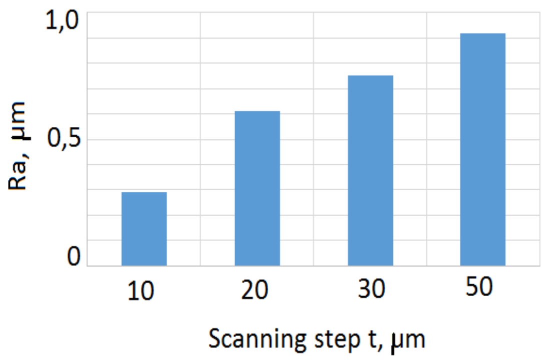


Fig. 5. The influence of the scanning step (t, µm) on the roughness of the samples (data for the scanning speed 150 mm/s).

Grain size

Our experiments with the low carbon steel model samples reviled that the larger the grain size of the metal the lover depth of ablation on the sample (Fig. 6). This could be explained by the assumption that larger grains (which corresponds to less volume of grain boundaries that would hinder the energy transfer) facilitates more intensive dissipation of the energy and require more laser energy on the material surface for the processes of deeper ablation to take place. Therefore they tend to have lover depth of ablation while the smaller grains “lock” more energy in smaller volume within the grain boundaries which act as a heat transfer brier.

At the same time the material with small grains having a reduced thermal conductivity which can cause the material to heat up more quickly during laser ablation. This can result in increased melting and vaporization of the material, leading to higher ablation depths (Fig. 7).

It should be emphasized that this outcome is associated with the studied material (α-Fe) and laser parameters described in previous section that could predetermine particular material removal mechanisms. This aspects may differ in other circumstances and other energy sources such as e-beam, magnetron field, etc. and are not subject of this study.

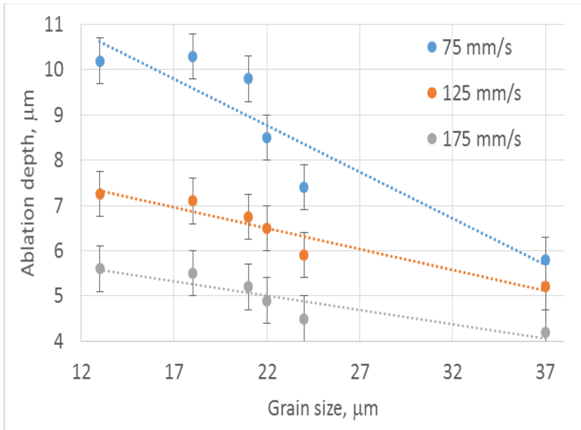


Fig.6. The influence of the grain size on the ablation depth of the samples.

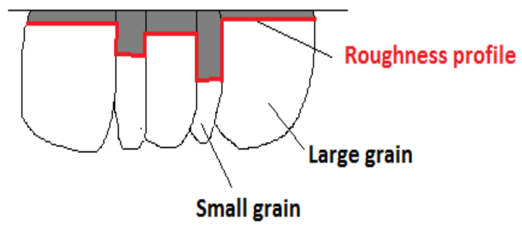


Fig. 7. Small v/s large grain ablation depth.

Modelling

To design the model representing the surface profile and the corresponding roughness calculation, we need initial experimental data on the influence of grain size on the actual ablation depth. This was done on the samples with different grain sizes obtained after the respective heat treatment described in the previous section. Laser processing was performed with 50 µm steps and 20 µm beam diameter to ensure minimal overlap and mutual influence of the neighbouring scanned areas. Thus the data presented on Fig. 8 was obtained and used to calculate mathematical model applicable at different scan speeds.

A linear regression analyses (with average correlation coefficient = 0.9) was performed for the data obtained at 75, 125 and 175 mm/s scanning speed. The general appearance of the formula is as follows:

$$\Delta\,[\mu m] = k \cdot d\,[\mu m] + b\,, \qquad (1)$$

where Δ - depth of ablation, d - average grain size, k, b - proportionality factor and free term.

Table 1 shows the values of the above parameters for different scan speed.

TABLE 1 PARAMETERS OF THE EQUATION

Scanning speed, v	k	b	Ra, μm model	Ra, μm experiment
75 μm/s	-0,2	13,3	0,55	0,60
125 μm/s	-0,1	8,5	0,37	0,41
175 μm/s	-0,06	6,4	0,28	0,30

This equations was then used to assign the ablation depth in respect of the grain size and to model by Monte Carlo method (as described in previous section) the surface profile of a low carbon steel with real grain size distribution (shown on the EXCEL model snapshot on Fig.1) after laser engraving. In this way, roughness profiles were generated (Fig. 9) and the corresponding mean roughness's at different scan speeds were calculated (Table 1). The results were compared (as a validation experiment) with actual measured samples, and it turned out that they differ from them by no more than 10%.

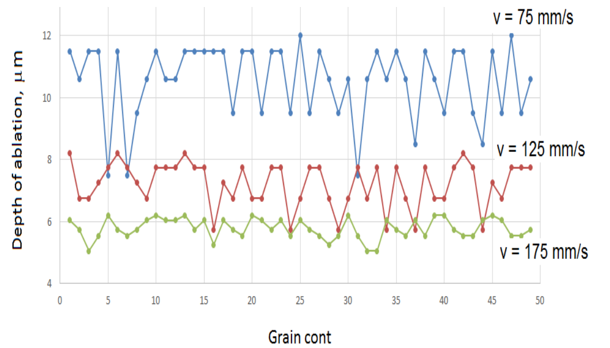


Fig. 9. Modelling the sample profile.

IV. CONCLUSIONS

It has been revealed that the scan speed and the step of scanning influence the depth of ablation and surface roughness (due to the change of density of the applied laser energy). The roughness increases by 100% when changing the scan speed from 75 to 200 mm/s and decreases by 50% when change the step of scanning from 10 to 50 μm.

The larger grains require more laser energy for the processes of ablation to take place. Therefore they tend to have lover depth of ablation while the smaller grains "lock" more energy within the grain boundaries and tend to have deeper ablation.

A Monte Carlo Model of the surface profile predicts the surface roughness of the samples depending of the grain size morphology. The model predicts the Ra value for the iron sample with 10% credibility.

V. ACKNOWLEDGMENTS

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