STUDY ON INFLUENCE SHARE OF TECHNOLOGICAL PARAMETERS REGARDING THE GLASS LASER ENGRAVING

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Abstract: The present present paper summarizes several theoretical aspects of the physical processes occurring in laser processing and also the study of the technological parameters' influence during laser glass engraving by using a design of experiments based on the Taguchi method. By using this method of experiment planning a small number of tests may be made, thereby meaning reduced costs. Following this study, results with a high scientific character will be obtained, in terms of influence of certain parameters on the size and shape of craters in high power laser processing of glass.
Key words: Laser, Parameters, Engrave, Crater shape.

1. INTRODUCTION

With a view to assessing the influence of some technological parameters of the process of LASER engraving of soda-lime glass, a plan of experiments on the shape and size of the formed crater has been developed, by using the Taguchi method (TM). This allows the assessment of influence of parameters in the process of high-power pulsed CO_2 LASER engraving process. The material used for this study is the normal window glass (float glass) of chemical composition of 70 SiO2, 10 CaO, 15 Na2O and density 2500 kg/ m3.

At the beginning of this written work there is a brief description of the complex phenomenon of laser engraving by highlighting the main physical processes that occur during processing. In terms of physics, the glass engraving done through this method is the action of the glass laser beam with a large amount of photonic energy converted into heat and affecting the crystalline structure of the material. During this manufacturing process, the glass goes from solid to liquid, followed by a solidification of some of the melted material, and a small amount is vaporized. Following these rapid changes, the laser processed area is being determined and characterized by changes in the microstructure of the matter surrounded by the heat affected area.

When laser interacts with glass, three types of physical processes occur and are largely dependent on the emission parameters of the laser source. These processes are:

Thermal processes manifested through heat transfer phenomena followed by heat conduction into the mass of material resulting thus the laser-processed zone and the heat affected zone;

Photochemical processes manifested through the photonic energy of the laser beam, which breaks the chemical bonds in the structure of the material. These processes take place over three stages with short-time duration. The first stage is characterized by the laser energy absorption of the glass surface subjected to processing. The second stage occurs by breaking chemical bonds in the material structure, and the third stage represents the removal of molten material fragments. Following these, the removal of material layers occurs vertically (see Figure 1);

Photomechanical processes occur as a result of using high power micro-second pulsed lasers and are manifested by matter local melting phenomena due to shock waves. This results because in the point of impact of laser radiation, the temperature is at its highest point and the pressure on the glass surface is minimal. When the laser beam stops the temperature drops, and the glass surface tension increases and spreads from the impact point to the edges. Thus the molten material moves from the center to the edges, causing a concavity in the drop. According to the statements of (Donţiu, 1985), the differences in the static pressure resulting from this curvature produce a return in shape of a wave that propagates from edges toward the center point of impact of the material with the laser radiation.

Evacuation of molten material and its vaporization is caused by the auxiliary gas, coaxial with the laser beam, or by the shock wave created when the plasma has been formed. Plasma is formed on the material surface due to the matter warming phenomenon and the emergence of a material stage characterized by high temperature after termination of the laser beam's action. Even if the power decreases after laser pulse termination, the amount of plasma is in a continuous movement and expansion caused by the shock wave.

Figure 1 presents schematically the action of the pulse laser beam on ceramics and glass. The most important elements and the areas where various processes described above occur may be seen below.

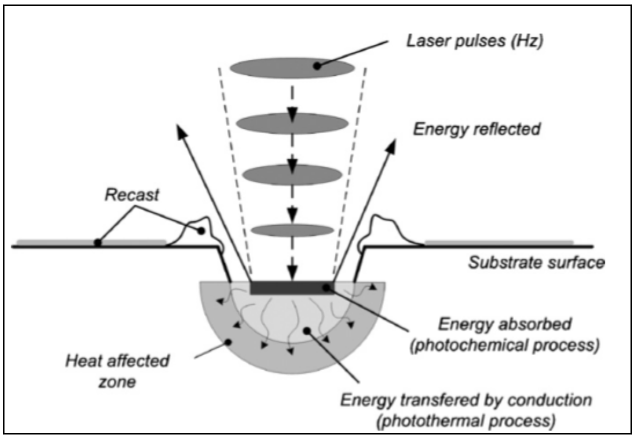


Fig. 1.The action of laser beam in pulse mode on ceramic materials and glass, [3]

For the study of thermo-physical interaction of laser beam with the glass, the next should be considered: the absorption degree coefficient and the beam reflection. These vary depending on the laser wavelength used in processing. There has been noticed that transparent calc-sodium glass, absorbs 94% from the laser beam, emitted by a CO2 laser generator with wavelength λ = 10.6 µm. The absorption coefficient may increase as the glass temperature subjected to processing increases too.

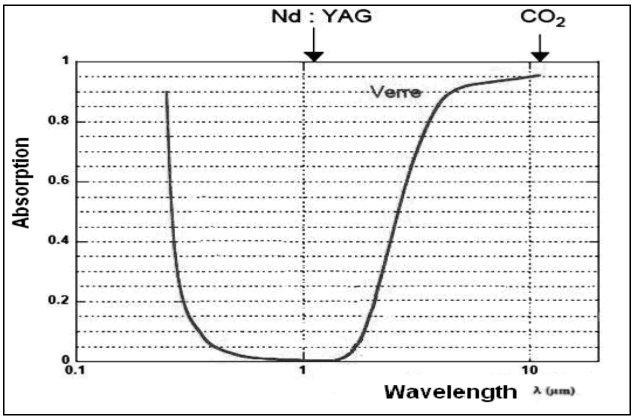


Fig. 2. Laser radiation absorption of the glass, depending on the wavelength, [1]

The quality of glass surface processed by laser engraving is influenced by the reflection degree of the laser beam, the absorption coefficient and the heat transfer into the mass of the material.
After presenting some certain theoretical aspects, this paper summarizes the influence share of technological parameters on laser engraving of glass, by using a design of experiments based on the Taguchi method. Research approach and result interpretation have taken into account the way of designing experiments previously by (Chen, 1996). For observing the influence of process parameters of Nd:YAG laser micro-engraving on glass with an iron oxide film, he used the same method.

2. A PRINCIPLED APPROACH TO THE PROCESS RESEARCH OF LASER ENGRAVING ON GLASS

The technological parameters of the glass laser engraving process to be studied are: the number of pulses (P1), the pulse duration (P2), and the LASER beam power (P3). In order to emphasize both the importance of these parameters influence and the interactions between them, according to TM a test plan is carried out, based on an L8 (2^7) orthogonal matrix. This one describes the order of technological parameter combinations for each test.
The principles of Taguchi Method of analysis used in this experiment are:

-choosing two reference levels of each technological parameter, so that when interacting with other studied parameters, according to the matrix layout principle, all the possible combinations may be made in an as limited number of tests as possible;
- identifying the importance of influence for every studied technological parameter and the interaction between those involved in the process of laser engraving on glass;
- depending on their share of influence – selecting the technological parameters on which further research will focus on.

The effect of laser engraving technology, characterized by different technological parameters, has major influences on the quality of the processed glass surfaces. Thus, the depth of the crater formed at the laser beam interaction with glass is an important feature in assessing the qualitative aspects of laser engraving on brittle material surfaces, like glass. The formed crater is practically the effect of the laser beam characterized by certain technological and physical parameters, interacting with the glass surface, causing surface warming, melting the layers, evaporation and solidification of the material. In this way, a very small cone-shaped crater can be obtained (see figure 1), being characterized by the following dimensions: depth of penetration h (height) and higher diameter D described in figure 3.

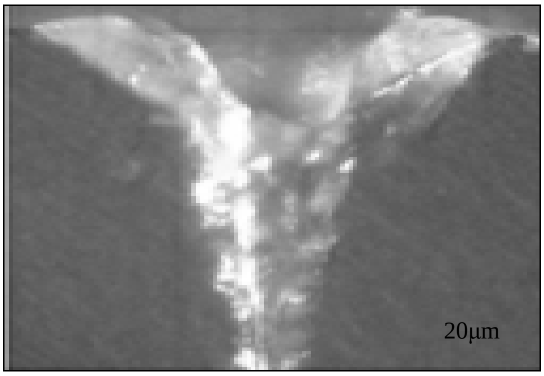


Fig.3. Sectional form the crater made by a Laser beam on glass

A key element in the use of laser systems operating in pulse regimes is the ability to control the emission characteristics. It is characterized by the following parameters: repetition frequency, pulse duration and pulse power.
The crater shapes and sizes are influenced by the geometry of a laser beam (divergence) and by the focus mode on a processing surface. They strongly influence the temperature distribution of a laser pulse in a glass material and the dimensions of the crater created depending on the laser spot diameter (Honma et al., 2008), as shown in Figure 4.

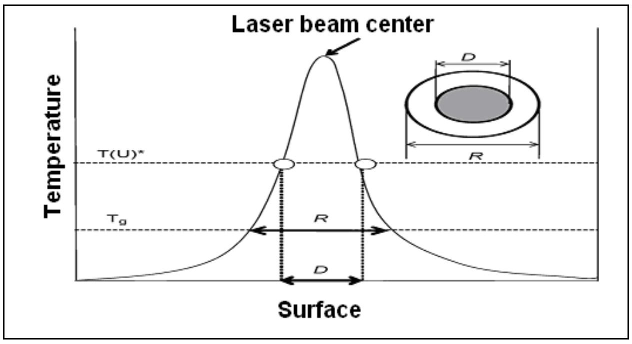


Fig. 4. Temperature distribution of a laser pulse in a glass material and the dimensions of the crater created contingent on the laser spot diameter, [5]

The laser beam geometry is defined by the TEM00 fundamental oscillation mode (TEM - a transverse electromagnetic mode) with Gausian radial profile.

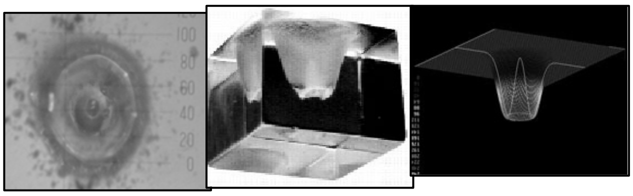


Fig. 5. Effect of Laser beam with Mode TEM 01* and grafical simulation on glass material

The laser beam and transversal electromagnetic mode profiles affect the energy distribution into the mass of the material. The laser beam with a TEM 01* mode is characteristic to the laser beam type of the LASER CILAS Alcatel CI 2000 equipment, used in this experiment.
Following the process of crater formation in the material, caused by the action of the high-power and short-duration laser beam, and due to thermal processes that occur, a heat affected zone will appear, surrounding the crater.
Based on previous findings of Breaban & Baurand (2009) who observed the evolvement of crater shape under the action of different intensity distributions of laser beam, followed by extensive research, a specific geometric shape of the crater has been identified, the crater being characterized by three zones with different shapes and weights, shown in figure 6.

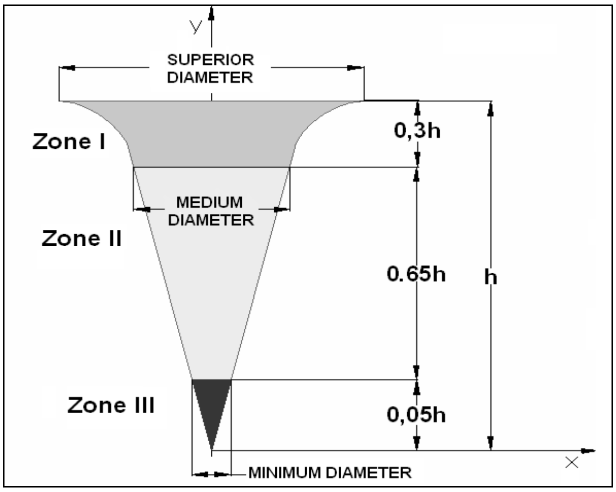


Fig. 6. Crater shape with its three characteristic areas

When interactioning with the laser beam, the crater formed in the mass of the glass material can be considered a geometric-shaped cavity around a body of revolution. Generally, these cavities address the following assumptions:
- the depth (h) of the crater is measured between the glass surface of the sample and the diameter at the crater base, which is usually half the upper diameter of the crater; see figure 2;
- we consider that the top of the crater, noted as Zone I, is approximately 30% of the total crater depth, i.e. 0.3 x h (depth);
- Zone II (see figure 2), from the structure of the crater, is about a regular truncated cone and weighs 65% of the total depth of the crater;
- the bottom of the crater, Zone II, is about a small straight circular cone-shaped, with a still weight of 5% of the total depth of the crater.
In order to calculate the theoretical volume of the three zones, we have adopted the mathematical modeling of the form. Looking upon figure 3 that expresses the graphical Gaussian shape modeling corresponding to Zone I, a lag parameter was arbitrarily chosen, equal to 0.01 x h. The equation of the desired profile will be marked with:

$$y = f(x) \quad (1)$$

The expression of f(x) will be Gaussian for y comprised between 0.01 x h and 0.3 x h, and for a regular shape y is comprised between 0.31 x h and 1.01 x h. The mutual function of "f" will be as follows:

$$g : x = g(y) \quad (2)$$

for a point (x, y) belonging to the profile.
To make calculation easier, the volume is calculated with the crater uside down (see figure 7); the hachured portion is not part of the cavity profile.

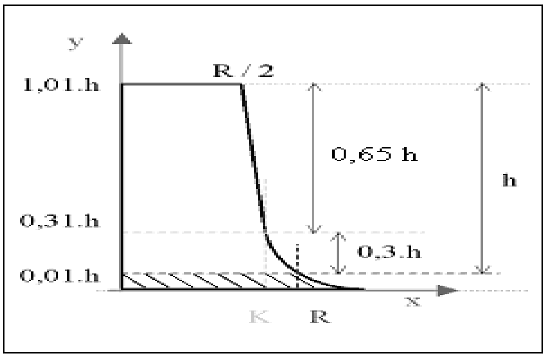


Fig. 7. The crater profile, turned uside down, the V_2 part for volume calculation, [1]

The total calculated volume of the crater is the sum of the volumes of each part:

$$V= V1+ V2 + V3 \quad (3)$$

Where:

- The value of V1 is obtained by using the deduced formula, which corresponds to the Zone I of the crater:

$$V_1 = \pi\beta^2 \cdot h\left[0.3\cdot(\ln\alpha + 1 - \ln(h)) + \lambda\right] \quad (4)$$

- The value of V2 is obtained by using the formula of the volume adjusted for Zone II, at the middle and regular shaped:

$$V = \pi\left[\frac{a^2h^3}{3}(1.01^3 - 0.31^3) + b^2h(1.01 - 0.31) + a\cdot b\cdot h^2(1.01^2 - 0.31^2)\right] \quad (5)$$

- The value of V3 is obtained by using the formula of the volume for the lower part of a straight cone-shaped crater:

$$V_3 = \frac{\pi R'^2 \cdot h'}{3} \quad (6)$$

3. DESCRIPTION OF THE EXPERIMENT AND THE RESULTS OBTAINED

For this experiment, we used the CILAS Alcatel IC 2000 LASER processing apparatus, in order to assess certain technological parameters of the laser beam operating on glass and producing craters of different shapes and sizes. According to the experimentation plan described by the Taguchi method, we have operated on 4 mm thick glass samples by using a laser beam characterized by the three parameters with different values for each test case.

Each of the parameters must have two imposed values, a minimum or a maximum one. These values are combined with each other during the eight test cases foreseen in the experimental planning matrix described in Table 1.

Description of the experiment main stages is shown in Table 2, where observations are provided for each stage.

Table1. Parameter values for each test

Test No.	Technological Parameters Value		
	Pulse Duration ti [ms]	Laser power P [W]	Number of Pulses
1	0.6	60	1
2	0.6	60	5
3	0.6	210	1
4	0.6	210	5
5	1.4	60	1
6	1.4	60	5
7	1.4	210	1
8	1.4	210	5

Table 2. Description of the stages of the experiment.

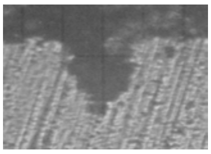
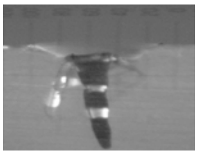
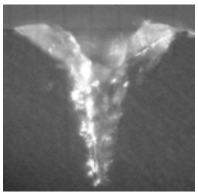
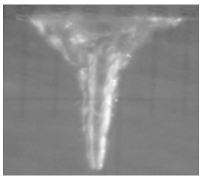
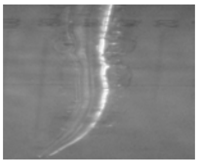
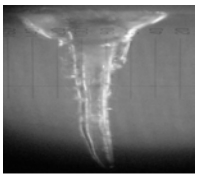
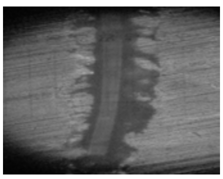
No.	Experimental stage	Observation
1	Glass sample processing by LASER pulses	The monitored technological process parameters are calibrated according to the experimental plan
2	Sample polishing	Sample polishing for observing the shape of the sectioned crate
3	Microscopic measurement Mitutoyo Quick Scope 359 and Shimadzu 341 with camera attached	Measurement of crater sizes (depth, diameters), shape visualization
4	Results assessment	

The results - following the measurement of the craters' depths and observation/study of their shapes after having operated on them by a laser beam with processing parameters set differently for each test - are presented in the Table 3.

Accomplishing this experiment by complying with a test plan developed by Taguchi Method has led to a relatively small number of trials implying low costs for materials and for the operational equipment involved.

The calculation way of this method provides for the graph of effects (figure 9) and interactions (figure 10) calculation and plotting, starting from each crater’s measured depth values.

Table 3. The resulted crater shapes according to the experimental design, the measured depths values, and the calculated volume values

Test/ Parameters (P2) (P3) (P1)	Crater images	Size Depth	Vol. Calc.
	Microscopic image	h [µm]	V [µm³]
1 ti=0,6 ms P=60 W Nr.imp. =1		63	23820
2 ti=0,6 ms P=60 W Nr.imp. =5		188	76257
3 ti=0,6 ms P=210 W Nr.imp. =1		140	68652
4 ti=0,6 ms P=210 W Nr.imp. =5		390	241444
5 ti=1,4 ms P=60 W Nr.imp. =1		203	66346
6 ti=1,4 ms P=60 W Nr.imp. =5		440	186399
7 ti=1,4 ms P=210 W Nr.imp. =1		340	221452
8 ti=1,4 ms P=210 W Nr.imp. =5		640	361551

In order to establish the graph of parameter effects (Epi) in comparison with the average depth, it is necessary to calculate the mean for each parameter at the minimum value marked with 1 and the maximum value marked with 2. Rule: each calculated Effect is added to the average Mean (M), and thus the effect is emphasized according to the general mean (Epi (1 or 2) + M).

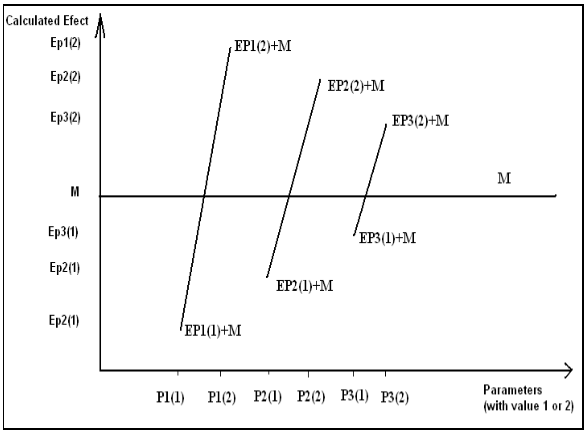


Fig. 9. Graph of parameters effect on crater depth

To observe the influence of interactions between studied parameters over the craters' depth, the study is based on the average value of the parameters with the two different values. According to a mathematical algorithm, there is the result of the value of the interaction between two parameters. These values are useful in tracing the graph of interactions between parameters, in order to see what their effect on crater depth is (see figure 10).

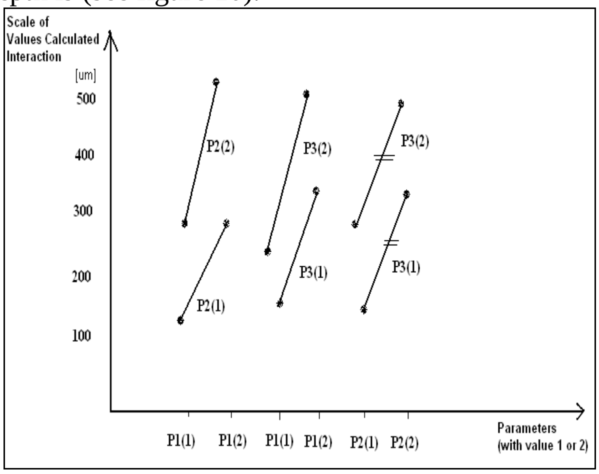


Fig. 10. Graph of Interactions between parameters

After plotting the graph of interactions between the studied parameters, according to the rules of interpreting the graphs determined by Taguchi method, with the aim of determining which of them has a bigger influence on the depths of the crater. It result that between the P1 and P2, P1 and P3 parameters there is interaction which has an effect over the crater depth. Between the P2 and P3 parameters there is NO interaction that could influence the depths of the craters formed by LASER beam on glass.

By using the calculation formulas of the percentage of the parameters influence over the craters depth established by the Taguchi analytical methodology, we have examined the influence percentage for each parameter studied in this experiment.
Thus, starting from the formulas of the sum of squared deviations (SCE) as shown below, where A, B are variable factors, we reach to calculate the percentages of the influence of each parameter on the crater depth.

$$SCE_A = \frac{N \sum_{i=1}^{i=n_A} E_{A1}^2}{n_A} \qquad (7)$$

N: is the total number of test results or the number of tests within the experience plan
n_A: the number of the level of the A factor

$$SCE_T = \sum_{i=1}^{i=N} (Y_i - \overline{Y})^2 \qquad (8)$$

Y: is the response obtained for each experiment (test)
$\overline{Y}$: the average values of Y
The calculation of the influence of each parameter on the depth of the crater:

$$\%Pm = \frac{SCEPm}{SCE_T} \times 100 \qquad (9)$$

In the last part of the experiment, we carried out the calculation of the percentage of parameters influence on the craters depths, and thus we obtained the values shown in the chart below *(see figure 11)*.

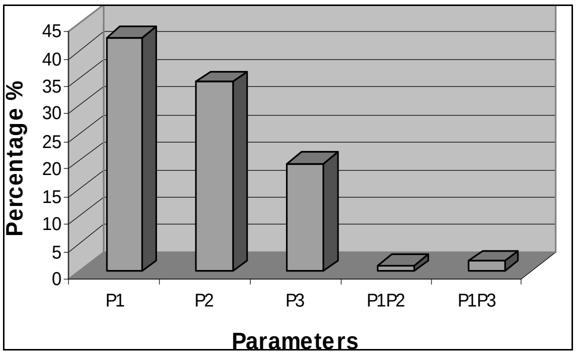


Fig.11. The influence percentage of the studied parameters, on crater depth produced by LASER beam operating on glass

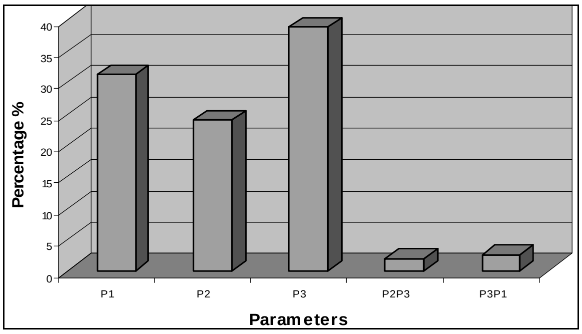


Fig.12. The influence percentage of the studied parameters, on crater volume produced by LASER beam operating on glass

By applying the same principles of analysis and route calculation method provided by Taguchi analysis, was made graphic presentation of the percentage of influence on crater volume for each parameter studied. It was noted that there is a different percentage disposition of technological parameters regarding influence of depth and volume craters

4. CONCLUSIONS

By performing this experiment in which we have used the Taguchi analysis principles, we have found the influence rate of certain technological parameters on the depths and volumes of the formed craters, implicitly, on the quality of surfaces subjected to laser beam action:
- the number of laser pulses applied to the glass surface has the largest influence percentage for depths, that is 42.5%, and for volumes it is 31.24%;
- the laser pulse duration applied to the glass has the percentage of 34.4% for depths and for volumes it is 24.02%;
- the laser pulse power applied to the glass surface has a minimum percentage of 19.6% for depths and for volumes has the largest influence percentage, that is 38.7%;
- the interactions ratio value of these parameters, P1P2 and P1P3, is of a negligible 1.77%, and 1.06% respectively.

As far as the three technological parameters are concerned, they will be evaluated in future research, with respect of their influence on the geometry of the crater shape and of the quantity of elevated material.

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