Discussions

Volume 2 | Issue 1 Article 5

2023

Parametric Study of a Nd Yag Laser Beam Interaction with Graphite

David Poerschke
Case Western Reserve University

Recommended Citation
Poerschke, David (2023) "Parametric Study of a Nd Yag Laser Beam Interaction with Graphite," *Discussions*: Vol. 2: Iss. 1, Article 5.
DOI: https://doi.org/10.28953/2997-2582.1078
Available at: https://commons.case.edu/discussions/vol2/iss1/5

Parametric Study Of a Nd: Yag Laser Beam Interaction with Graphite

-David Poerschke-

David Poerschke is a second year student from Ligonier, PA. He is studying Materials Science and Engineering. In addition to his studies, David takes an active role in both his department and the university. He currently holds a research position in the Case Metal Processing Laboratory. His primary work in the lab is operating an Nd:YAG laser.

-Acknowledgements-

The USAF Air Force DURIP Equipment Award and the sponsorship of the Case SOURCE program for this investigation are gratefully acknowledged.

ABSTRACT

Graphite is an important material in a number of specialized industrial applications due to its high thermal conductivity and resistance to thermal shock. Common applications include use as an electrode in electro discharge machining and as a mold material in metal casting. These applications often include fine details that are difficult to achieve with rotary tool machining techniques. Ablation with an Nd:YAG laser marking system permits greater detail in the machined pattern. The beam behavior and resultant mark are determined by four key operating parameters: lamp current, pulse frequency, marking speed and pattern repetition. Experiments were conducted to determine the effect of each parameter on the rate of material removal and resulting mark quality. Scanning Electron Microscopy (SEM) was employed to characterize the mark quality. Results were analyzed to determine the most efficient parameter without degrading the quality of the mark. Reducing the marking speed had the most profound effect on the material removal rate.

INTRODUCTION

Laser applications in material processing are becoming ever more common. Increased processing speed, low operating cost, and greater capabilities make laser ablation a viable alternative to traditional mechanical machining technology. This study analysed the impact of a number of operating parameters on graphite, an important material in several manufacturing methods.

One of the most notable applications of graphite is as an electrode for Electro Discharge Machining (EDM). EDM is a highly precise method of machining numerous materials. An electrode is placed close to the material surface with a dielectric liquid filling the void between the two. A current is passed through the electrode to create a controlled pattern of arcs that erode the material. The electrodes used can vary both in size and material. Often, a graphite electrode is machined so that it is a negative image of the desired pattern. Graphite is also used as a mold material for metal casting and rubber molding. High thermal conductivity and resistance to thermal stresses make it an ideal choice.

In both cases, the pattern is often limited by the size of the rotary tools available. This issue is especially troublesome when attempting to cut inside corners. The non contact nature of laser ablation eliminates these concerns.

The tests conducted fell into two categories. First, the depth of focus for the beam was determined to ensure that further testing would take place with adequate fluency. For a given set of optics there is a focal length that will maximize the beam fluency. Unfortunately, as material is removed the focal length changes. Optimally the worktable can be raised to compensate for the removed material, but this is not always possible. Alternately, a depth of focus where the laser energy is sufficient to ablate material can be determined. As long as the depth does not exceed the depth of focus, marking is possible.

The second class of tests was designed to determine the impact of the key operating parameters lamp current, marking speed, pulse frequency, and pass count on the efficiency of material removal. The selection of a parameter set involves a number of tradeoffs between time, cost, and quality. By developing relationships between parameter choice and result, it will be easier to choose the best configuration to complete a job.

EQUIPMENT

Testing was conducted using a pulsed 100W Nd:YAG laser marking system. This system consisted of the laser, interchangeable focusing lenses, and a set of computer controlled mirrors used to direct beam across workpiece. The system is mounted in a machine base with three axis workbench. This bench is equipped with a two dimensional digital readout system displaying table position. This system allows the user to measure small, precise adjustments made in the sample location before, during, or after marking.

A proprietary software suite called FobaGraf was used to define beam path. Using a simple programming language, the software gives the operator complete control over a number of important laser parameters including lamp current, marking speed, pulse frequency, as well as the number of passes that should be taken over the pattern. The software allows simple paths to be programmed. For more elaborate patterns, a tool is included to import CAD or other vector artwork files. Patterns used in these tests were all created in AutoCAD and imported.

PROCEDURE

Depth of Focus

To determine the depth of focus an apparatus was designed to allow the focal length to be systematically adjusted. The apparatus consisted of an angled bar attached to the work table. A strip of painted steel was clamped to this bar. The laser scribed a short line on the metal strip and the entire table was then translated so that the next mark would be at a different focal length. Figure 1 shows this arrangement. The apparatus was designed so that each 1mm of table movement was equivalent to a 100μm change in focal length. After marking, the strip was sectioned and examined using scanning electron microscopy. Images of the lines were obtained. Using Photoshop, the width of each line was determined. When measuring this width, both ablated metal and any disruption of the paint were included because at greater focal lengths the only mark appears on the paint.

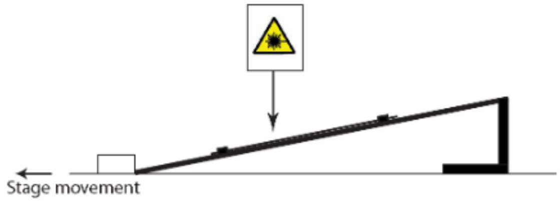


Figure 1: Focus Testing Apparatus

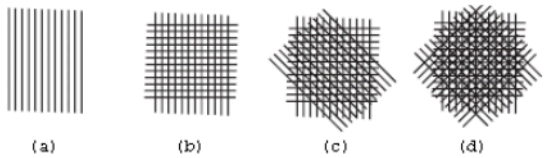


Figure 2: Hatch Patterns

Material Removal

A series of patterns were developed to test the effect of laser parameters on the efficiency of material removal. The patterns consisted of roughly 30 2mm squares. Each square was assigned a different parameter set based on the variable in interest. These values were chosen to provide a representative picture of the laser's capabilities. The focal length was chosen so that the entire depth of the square fell within the depth of focus for the system. To minimize any adverse effects associated with temperature rise in the sample material, the laser was paused briefly between squares and the squares were marked in a non-sequential pattern so that adjacent squares were never marked consecutively.

After the sample was ablated, the depth of each square was determined with the aid of a Mitutoyo digital indicator. This experimental routine was repeated on several metals to provide comparison to engineering materials traditionally processed with lasers.

Surface Finish

When the desired pattern requires the ablation of a 2D area, the area must be hatched with a series of lines to fill the area. The marking software provides a range of options to generate this hatching pattern. The most important parameters are the spacing of the hatch lines and the orientation of one or more planes. The ideal spacing between lines is the laser spot diameter. This spacing was used in conjunction with the four hatch patterns shown in Figure 2 to generate a range of surface finishes.

RESULTS AND ANALYSIS

Depth of Focus

Figure 3 The line width obtained is proportional to the laser spot size and therefore indicative of how well the beam is focused [1]. In the region close to the focal length of the optics, a smaller spot size indicates a well focused beam. The experimental line widths obtained are shown in Figure 3. Most researchers consider any beam width within $\sqrt{2}$ of the beam width at the focal point to be within an acceptable depth of focus [2] [3].The average line width for the roughly flat region at the bottom of the figure is 212μm. Based on this figure, it was determined that any focal length that produced a line smaller than 300 μm falls within the depth of focus. This includes all lines with measured focal length of 125.5mm to 131.6mm. Based on this knowledge, makings up to 6mm in depth could be created without noticeable loss of power. The user would focus the material to 125.5mm to maximize the depth possible.

Material Removal

Figure 4 is a comparison of material removal rates for a range of materials. These relationships can be used as a guide to appropriately scale the results presented below for other materials.

Lamp Current: The laser energy is supplied by a high pressure krypton flash lamp. The light from this lamp is used to excite electrons in the Nd:YAG rod to start the chain reaction resulting in a laser pulse. The output power of the laser is directly proportional to the output power of the lamp, which is in turn controlled by the current supplied to the lamp. The output power should increase with the square of the current. This relationship is shown in Figure 5. It can also be noted that the laser did not have enough power to remove material until the current reached 17A and then follows a roughly parabolic pattern. The lamp current is independent of time, making high current processing most time efficient. It was also observed, however, that since more energy is imparted in the same amount of time, there is a greater likelihood that thermal damage will occur. Although observed less frequently on graphite, these thermal impacts must factor into the decision on what current to use.

Pulse Spacing is based on the relationship between pulse spacing and marking speed. The two parameters must be balanced so that each spot overlaps the previous to form a solid line. This result is obtained with any combination of the parameters such that the translation of the beam between pulses is less than the spot size. With increased overlap, more material is removed per unit distance covered. Although this increases the amount of material removed per pass, the time it takes to complete the pass is increased. In addition, pulses produced at high frequency contain less energy than lower frequency pulses. Figure 6 shows the results these trials. Based solely on the measured depth, it appears that the rate of material removal can be maximized by choosing a low marking speed. In reality, however, there is a strong time dependence in the data. It takes significantly longer to complete a marking at 5mm/s than at higher speeds. To correct for this inherent time dependence, the data was normalized to a marking speed of 200mm/s, the rate used for all

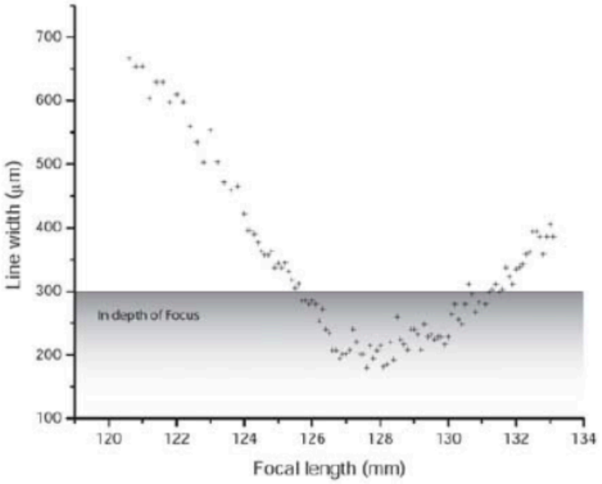


Figure 3: Measured Line Widths

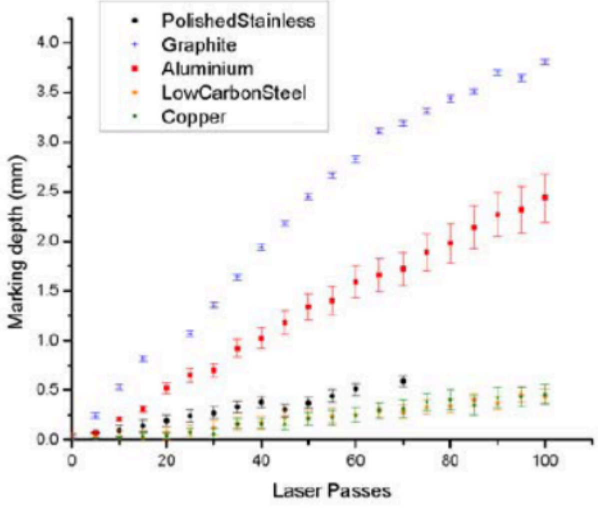


Figure 4

other tests. It then becomes clear that there is little change in actual material removable rate as the marking speed is changed and the normalized depth of approximately .6mm corresponds well to that obtained with a 28A lamp current.

Pass Repetition: Once configured, the control system can be instructed to repeat the marking as many times as are needed to achieve the required depth or until the depth of marking is greater than the depth of focus. The pattern was run twice. The first set of data used hatch

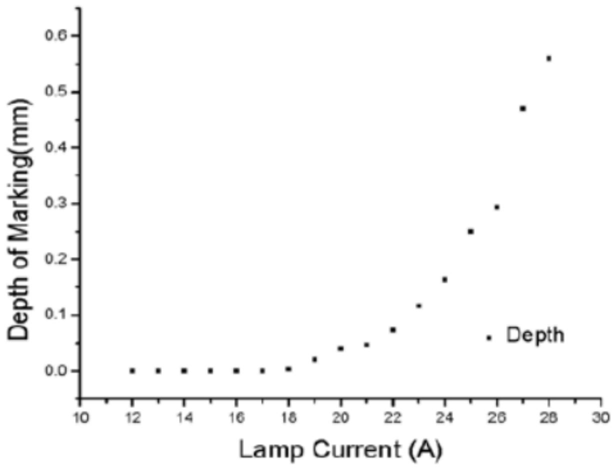
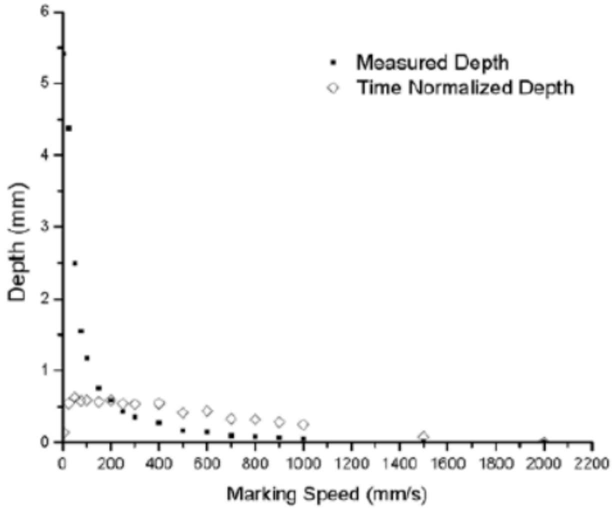


Figure 5: Increase in lamp current causes nonlinear increase in marking depth.



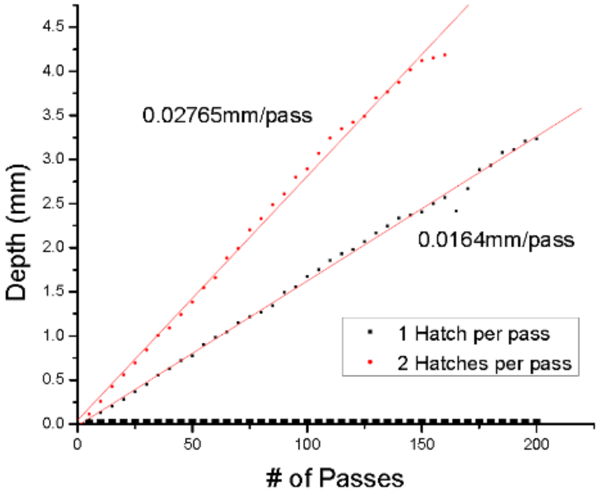


Figure 6: Increasing pass repetition increases the depth of marking.

pattern in Figure 2a. The second test was run with the pattern in Figure 2b. Figure 7 shows this data, accompanied by the slope of the respective tests. It is expected that since twice the number of passes are taken in the second configuration, the material would be removed at twice the rate. Contrary to this hypothesis, the experimental results showed an increase of only 70% in the rate of material removal. It is seen that increasing the number of passes increases depth, but there is again an introduced time factor in the data. The actual rate of material removal is derived from the slope of this line, and is therefore constant. One advantage of the of the linear nature of this parameter is that the final depth can easily be controlled by increasing or decreasing the number of passes.

Surface Finish

A WYCO non-contact optical surface profilometer was used to characterize the surface of the four hatching regions. Due to the low reflectivity of graphite, a thin layer of gold was sputtered onto the surface. Figure 7 shows the surface profile generated by the hatch patterns as well as an SEM image of one region in Figure 8 . Table I contains quantitative data from this analysis.

The complexity of the marking increases in proportion to the number of hatch orientations. As more layers are added, especially at non right angles, the pattern takes longer to process due to the extra beam translations required. In addition, the likelihood that the hatch pattern will not align perfectly with the edge of the marching increases with the number of layers marked. This can be seen in Figure 9.

Based on these criteria, it is desirable to choose the hatch style with the fewest layers to mark the pattern. Examination of Figure 7 shows that if only one orientation of hatching is used, the resulting pattern has a series of high ridges and deep valleys. By adding perpendicular hatching, these high ridges are knocked down. This is enforced by the largest Rq (root mean squared roughness) value for the single hatch. The least rough of the patterns was the area marked with the two layer cross hatch, making this a an ideal choice for hatching.

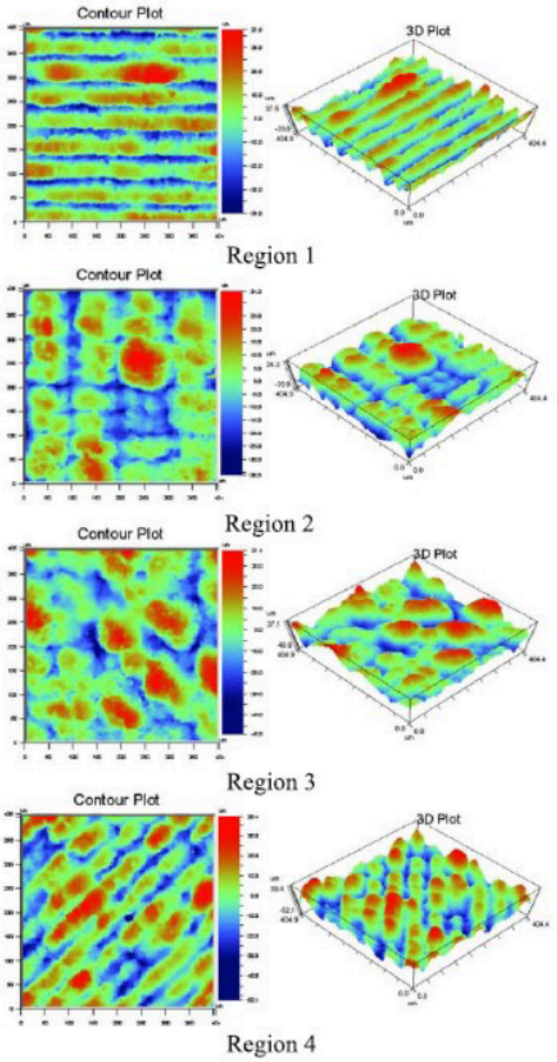


Figure 7: Images or four hatch regions examined.

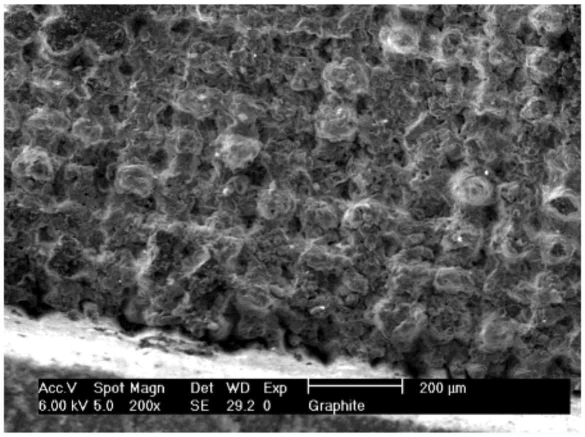


Figure 8: Graphite marked with hatch pattern in Figure 2 (b)

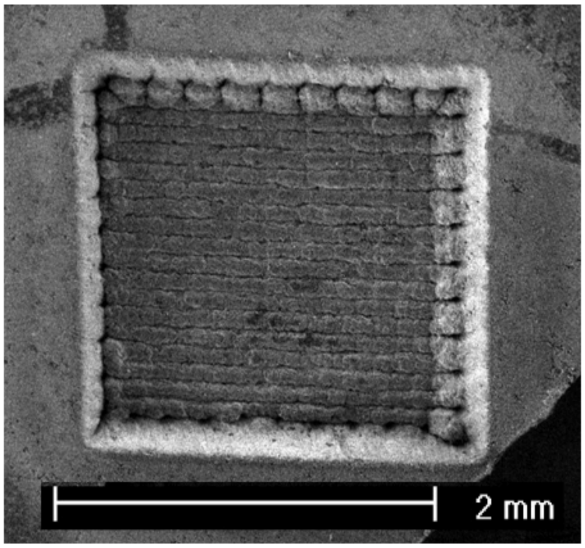


Figure 9: Hatch pattern did not remove material along upper and right borders of object.

CONCLUSIONS

While increasing capability in design is an important motivation in choosing laser ablation as a method of machining graphite, the driving factor is always cost. The key controllable variable in the cost of machining is the time it takes to run the pattern. Of the three key operating parameters, current is the only parameter that allows for time independent increase in the material removal rate. Increasing pattern repetition or reducing marking speed also increased the depth of the markings, but also led to longer processing times. By adding additional orientations to the hatch pattern the ridges and valleys generated can be broken up, but the effect is most pronounced with two hatch directions offset by 90°.

Sample	Rq (µm)	Rz (µm)
1 (Pattern a)	13.08	75.27
2 (Pattern b)	10.36	63.96
3 (Pattern c)	12.06	74.92
4 (Pattern c)	12.1	76.47

Table I: Rq (Root Mean Square Roughness) and Rz (Maximum peak to valley separation) of the four hatch patterns analyzed.

REFERENCES

[1] Nonhof, C.J. Material processing with Nd-lasers, Electrochemical Publications. (1988)

[2] Ion, John C. Laser Processing of Engineering Materials, Elsevier/Butterworth-Heinemann. (2005)

[3] Miller, J.C. and Haglund, R.F Laser Ablation and Desorption, Academic Press. (1998)