AC 2009-2149: A LASER MICROMACHINING D.O.E. TO INVESTIGATE MATERIAL REMOVAL VOLUMES

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A Laser Micro-Machining DOE to Investigate Material Removal Volumes

Abstract

This paper presents the results and lessons learned from a design of experiments (DOE), developed to better understand the factors that affect volume of material removed (MRR) during a laser micro-machining process. The Oxford Laser micro-machining center was brought into the Engineering & Technology Department's laboratory to be used for precision part marking and laser machining on the micron-level. The laser has a 0.1-µm precision in the x-y plane—about 0.2% of a human hair diameter. It has 5-axis CNC (computer numerical control) capabilities with dual wavelength capability—a 266-nm laser and a 532-nm laser—and can machine via the CNC axes or the high-speed galvanometers. These high-end capabilities, coupled with many other "bells and whistles" make this laser machining center highly versatile. In this research, a four-factor full-factorial DOE was performed to gain a fundamental understanding of the input parameters necessary to micro-machine 301 stainless steel. The four factors investigated in this research were power, frequency, hatch spacing, and feed rate; the output variable was volume of material removed. While frequency, closely followed by power proved to have the greatest effect on the output, none of the main effects or interactions proved to be statistically significant. The DOE results from this research were used as examples in a new senior-level quality course, which introduces DOE as a subject to senior Engineering Technology students. The real life DOE results provide a powerful classroom advantage to the typical textbook data, in that students see the real-life application more readily. The next step in this research is to refine this particular DOE and transition into regression analysis, where a mathematical model can be generated to predict (and control) the volume of material removed.

Introduction

Western Carolina University (WCU) is a comprehensive state university situated in the mountains of western North Carolina - with approximately 9,000 graduate and undergraduate students. WCU serves a region that continues to employ heavily in the manufacturing sector, which ranks number one with 19.3% of all jobs in the western portion of the state[1], which is why the Engineering Technology (ET) program continues to prepare its graduates through both its on-campus and distance education degree programs. The ET program exposes its students to a multitude of industry-related courses, including CAD/CAM, polymers, rapid prototyping, fluid power, numerical methods, occupational health and safety, automation, and quality. The adoption of Six Sigma techniques in the past decade has placed a high priority on quality in the workplace, and accordingly in the classroom[2].

The Engineering Technology curriculum recently added a senior-level undergraduate quality course (Advanced Quality Systems) to follow the junior-level Quality Systems course. A more in-depth quality course, Quality Assurance, is available to the graduate students at WCU. The addition of the senior-level quality course has given undergraduate ET students the chance to dig deeper into quality topics such as design of experiments (DOE) and regression analysis—both highly desirable tools in industry.

The ET students in this program tend to prefer hands-on experiences in their learning process. As a result, many of the courses are lab-based, but for those that are not, it is desired that in-class demonstrations reinforce the topics at hand. The ET majors have been exposed to a variety of industrial equipment and processes that are immediately applicable in industry, such as rapid prototyping (Stratasys FDM Titan®, Stratasys Eden 333®, ZCorp Z400®); flexible gaging (Zeiss Contura HTG® Coordinate Measuring Machine (CMM), OGP SmartScope Flash 200® Video Measuring System, ADE Phase Shift MicroXAM® surface mapping microscope); computer numerical control (CNC) machining (HAAS® 2D Laser Cutting Center, Four HAAS® Milling Machines, Three HAAS® Lathes); and CAD/CAM (50 Dell® Model , 21" LCD Monitors, PRO/ENGINEER Wildfire®). This research focuses on the capabilities of one of the newer pieces of equipment in the laboratories—an Oxford Lasers Micro-Machining Center.

Overview of Laser Machining Center

The laser machining center (Figure 1), supplied by Oxford Lasers of Oxford, England, was acquired for its micron-level precision capability of machining and marking materials ranging from polymers to super-alloys.

Figure 1: Oxford Laser Micro-Machining and Part Marking System

The laser includes features such as[3]:

- The laser is a diode-pumped solid state laser; it uses a medium that is solid, rather than a gas, such as CO_2.
- There are two lasers on-board: a 266-nanometer (nm) and a 532-nm wavelength head for processing softer materials (polymers, plastics, and glass) and harder materials (metals and ceramics), respectively.
- It has five-axis CNC control for three-dimensional machining: x- and y-axis control of the table in the horizontal plane, z-axis control of the laser's vertical position, b-axis rotation about the y-axis, and c-axis rotation about the z-axis.
- Galvo scanning heads provide the capability of laser machining inside a workspace of 50 by 50 mm without using the CNC stages; this allows for much higher-speed machining, since the workpiece remains stationary.
- The beam can be focused to a spot size adjustable between 6 and 24 microns (μm) with CNC axis resolution at 0.1 μm. This provides the capability of micron-level high-precision machining. A human hair is typically on the order of 50 to 100 μm in diameter.
- Two solid-state cameras assist in precision alignment, while two additional solid-state cameras provide access to view the machining process during operation.
- The PC drives three LCD monitors. A fourth LCD monitor is used to display the image projected by one of the two cameras in the workspace.
- It is a completely enclosed class I system which means that when all doors and interlocks are closed, the laser is completely safe to be around.
- Inside the enclosure, the machine has its own fume extraction system where no tubes or vacuums are vented to the outside.
- The system is capable of encoding and decoding two-dimensional barcode (i.e., data matrix) information. An additional camera is dedicated to reading data matrices, generated either on the laser or externally.
- To control the laser beam, CNC stages, galvo heads, viewing cameras, barcode reading camera, and alignment cameras, a total of five different software programs are needed. JWIN controls the power and frequency of the laser; MV2 controls the barcode reading camera; Waverunner controls the Galvo heads; Aerotech controls the CNC stages; and Powermill is a CAD/CAM package that is needed to manipulate models. Waverunner can only create two-dimensional features and works only by using the Galvo heads. In order to write programs to perform four- or five-axis machining, Powermill must be used.

The initial efforts on this relatively new machine were to explore its part-marking capabilities, including part identification, serialization, data encoding, etc.—essentially any markings that go directly on a component[4]. These part marking capabilities, while useful, did little to explain the ability of this laser micro-machining center to remove specified volumes of material, such as that required in machining micro-fluidic channels for biomedical applications. This research focuses on the investigation into the material removal aspects associated with this Oxford Laser.

Figure 2 shows a portion of a specimen machined in this research. The capital letters in the text are 2 mm in height.

Figure 2: 301 stainless steel machined on Oxford Laser

Figure 3 shows a hole and its label on the workpiece. The details of the numbering and hole specifications are explained later in this paper.

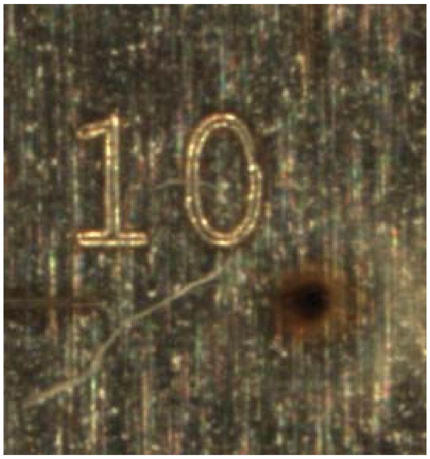


Figure 3: Optical microscope view of Hole #10

Design of Experiments

One of the most powerful tools used during the *analyze* phase of the six sigma process is the design of experiments, commonly known as DOE. The purpose of a DOE is to determine the effect, if any, of multiple inputs on a given output, as well as any interaction effects due to a combination of two or more of those outputs. The concept of DOE was first developed by R. A. Fisher in England in the 1920s, but due to the complexity of dealing with large numbers of variables, it did not gain wide usage until recently[5]. Software allows the user to deal with many input variables, as well as multiple output variables.

The basic premise of a DOE is to measure some output (y) as a continuous variable (i.e., it can take on many values over a given range). The inputs (x_1, x_2, x_3, etc.) are varied discretely. In other words those inputs are given a high and a low value (sometimes a middle value is used, as well, but not in this particular paper). The reason for this discrete variation is to minimize the total number of possible combinations of the input variables; a 3-input DOE has eight ($2^3 = 8$) possible variations, if each input takes on just two different levels. Typically, each experimental run is repeated for a given combination of input variables; this is called replication and it minimizes the effect of process variability[6].

When many inputs are introduced, the number of possible combinations is compounded and can become quite time-consuming and/or expensive to complete the DOE. For example, a 6-factor DOE has 64 combinations ($2^6 = 64$), and if just three replicates are used, there are 192 experimental runs necessary. This can become quite expensive if material, machine, or laboratory costs are high. This introduces the concept of a factorial design. A DOE that uses all possible combinations is called a full factorial design. A DOE that tests only half the combinations is called a half-factorial design, and so forth. The advantage to the half-factorial and other fractional-factorial designs is that it reduces the number of experimental runs needed for the analysis. The disadvantage to the fractional-factorial designs is that higher order interactions are lost.

Interactions are the result of some combination of two or more factors having a greater effect than any single factor. The classic example is the volatility of a chemical solution including vinegar and baking soda. Neither the vinegar nor baking soda is especially volatile, but when combined, they cause quite a reaction. For the purposes of this DOE, fractional factorial designs were not explored, and thus the ability to detect higher order interactions was not lost.

Design of Experiments for the Volume Removal

In this paper, four input variables were considered: power, frequency, hatch, and feed rate. The input variables were assigned as shown below, with low and high settings as noted:

Variable	Low	High
x_0 = Power	0 = 70 %	1 = 85 %
x_1 = Frequency	0 = 10 kHz	1 = 40 kHz
x_2 = Hatch Spacing	0 = 0.002 mm	1 = 0.010 mm
x_3 = Feed Rate	0 = 10 mm/s	1 = 100 mm/s

Hatch spacing is the distance between lines when the laser fills in a space that has been outlined, such as the circle that is to be machined into a hole. The power is a percentage of full power. The feed rate, also known as pen speed, is essentially the linear speed at which the laser beam moves along the surface of the workpiece. The frequency is the rate at which the laser pulses.

The following machine parameters remained constant throughout this DOE:

- Laser Beam: 532 nm
- Beam movement: Galvo
- Hole diameter: 50 µm (nominal)
- Hatches used: spiral (concentric circles)
- Focus height: -20.50 mm from top of table
- Loop count: 75 (number of times the beam passes over a feature)

The output variable, y, was the volume of material removed, measured in cubic microns (μm^3). Table 1 shows the settings for each variable for this four-factor two-replicate full-factorial DOE, as well as the resulting values for the output variable. The volume was measured, using a ADE Phase Shift MicroXAM® surface mapping microscope, which employs white light interferometry to map the surface contour. A three-dimensional view of one of the holes is shown in Figure 4.

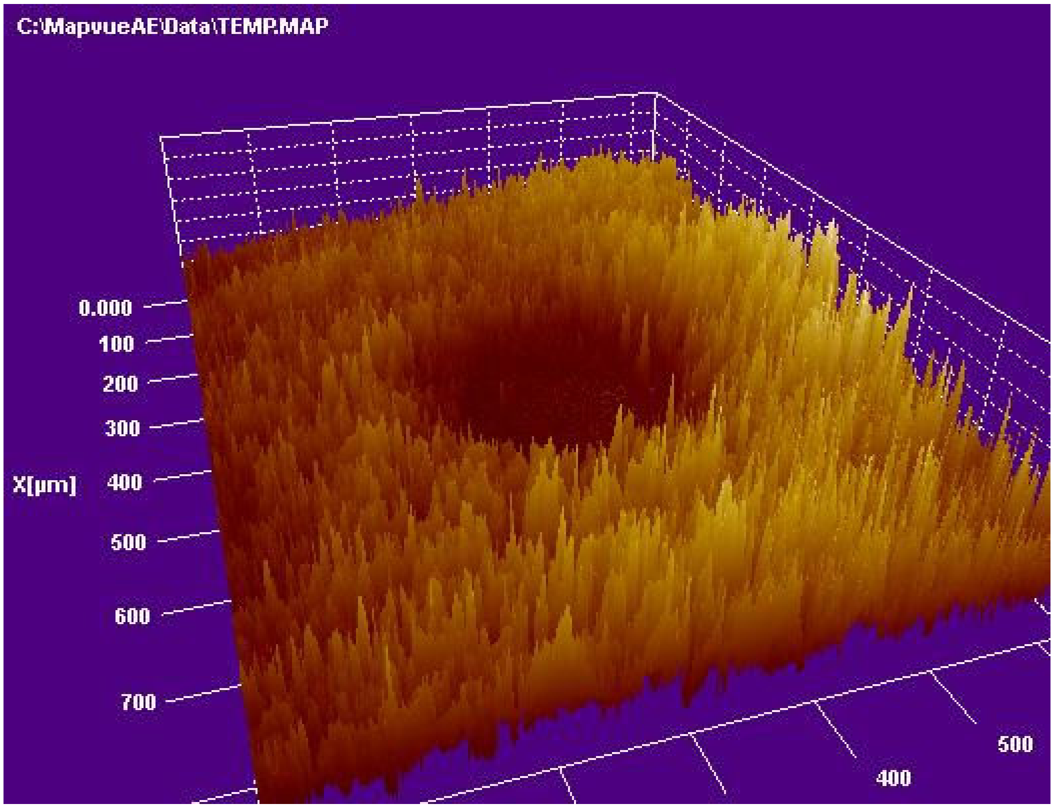
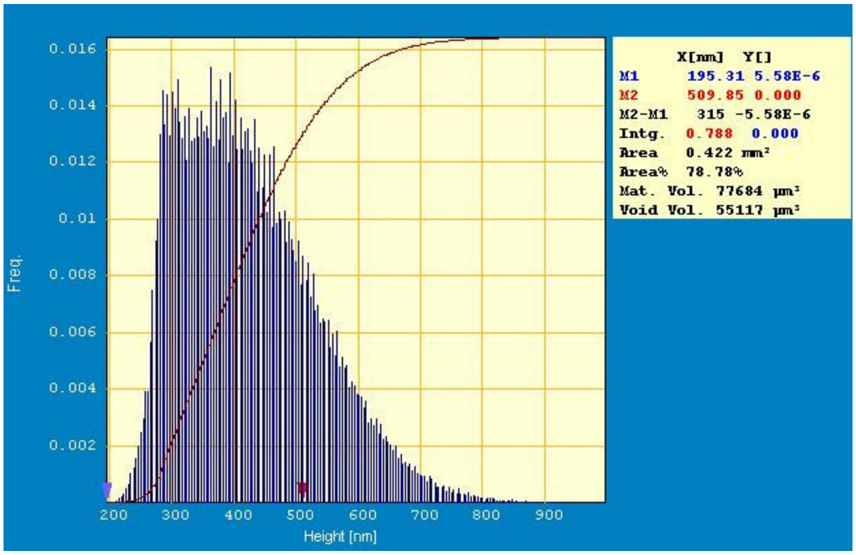


Figure 4: Hole #1 – 3D view

This surface profiler assigns a vertical height to each pixel representing the surface in the field of view. The heights of these pixels are then used to generate a histogram and corresponding volume of a negative feature—in this case the hole. Figure 5 shows such a histogram with the volume calculated as 55,117 μm^3, or 55.117 x 10^3 μm^3.



```
        X[nm]  Y[]
M1      195.31 5.58E-6
M2      509.85 0.000
M2-M1    315 -5.58E-6
Intg.  0.788  0.000
Area   0.422 mm²
Area%  78.78%
Mat. Vol. 77684 µm³
Void Vol. 55117 µm³
```

Figure 4: Hole #1 – histogram and volume calculation (void vol.)

Table 1: DOE data

	Hole #	x0	x1	x2	x3	y
Std Order	Run Order	Power	Frequency	Hatch	Feed	Volume (x10^6 µm^3)
6	25	1	0	1	0	51.087
14	21	1	0	1	1	54.338
4	31	1	1	0	0	47.676
2	32	1	0	0	0	71.538
8	27	1	1	1	0	45.007
12	28	1	1	0	1	46.402
3	22	0	1	0	0	37.522
7	17	0	1	1	0	24.137
16	18	1	1	1	1	43.477
10	29	1	0	0	1	60.005
1	24	0	0	0	0	31.200
9	20	0	0	0	1	63.030
13	26	0	0	1	1	44.661
15	19	0	1	1	1	43.604
11	30	0	1	0	1	30.552
5	23	0	0	1	0	46.674
22	10	1	0	1	0	70.889
30	6	1	0	1	1	29.475
20	3	1	1	0	0	37.378
18	14	1	0	0	0	54.523
24	1	1	1	1	0	55.117
28	8	1	1	0	1	23.793
19	16	0	1	0	0	30.650
23	15	0	1	1	0	79.317
32	13	1	1	1	1	37.818
26	9	1	0	0	1	67.629
17	5	0	0	0	0	19.929
25	12	0	0	0	1	40.480
29	11	0	0	1	1	69.840
31	2	0	1	1	1	25.308
27	7	0	1	0	1	25.604
21	4	0	0	1	0	29.763

The data for this DOE were analyzed using Minitab version 15. The main effects plot, shown in Figure 6, indicate that frequency, followed closely by power, has the largest effect on the output variable. The p-values for each of the main effects and interactions were as follows:

```
Estimated Effects and Coefficients for Volume (coded units)
Term                              P
Constant                      0.000
Block                         0.623
Power                         0.095
Frequency                     0.065
Hatch                         0.480
Feed                          0.764
Power*Frequency               0.406
Power*Hatch                   0.238
Power*Feed                    0.206
Frequency*Hatch               0.336
Frequency*Feed                0.141
Hatch*Feed                    0.366
Power*Frequency*Hatch         0.482
Power*Frequency*Feed          0.126
Power*Hatch*Feed              0.938
```

Using an alpha value of 0.05, none of the main effects had a statistically significant impact on the output variable. A slightly higher alpha value of 0.07 would yield a significant main effect with regard to frequency. None of the first-order or higher-order interactions proved to be statistically significant. The first-order interactions are shown in Figure 7. The interactions that are most significant are those with large differences in slope (i.e., parallel lines show no significance in interactions).

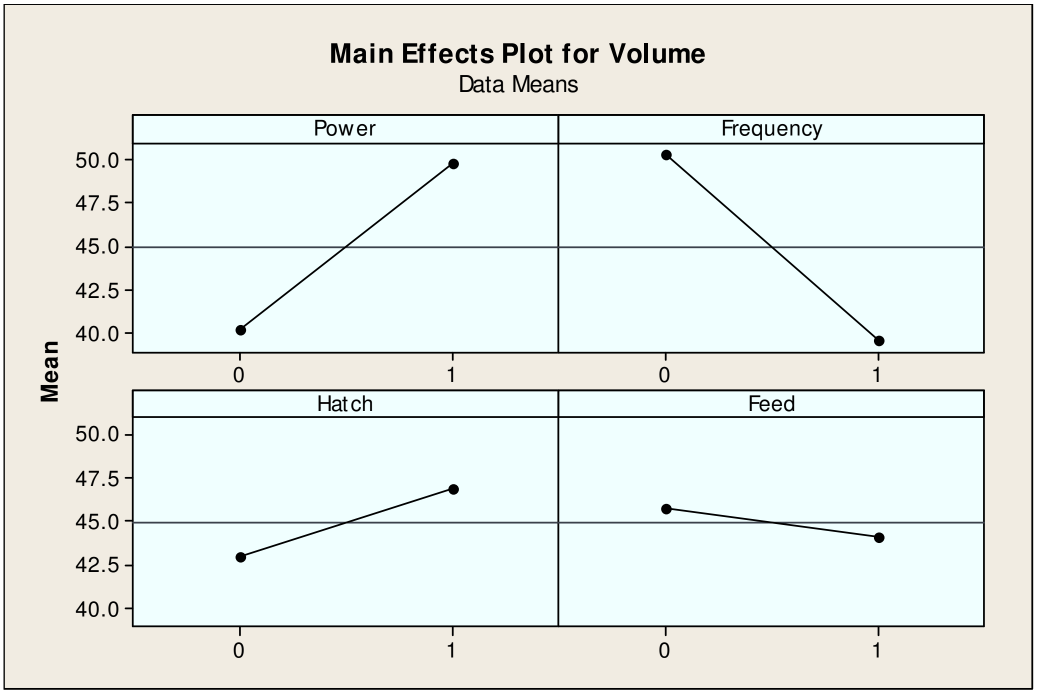


Figure 6: Main effects plot

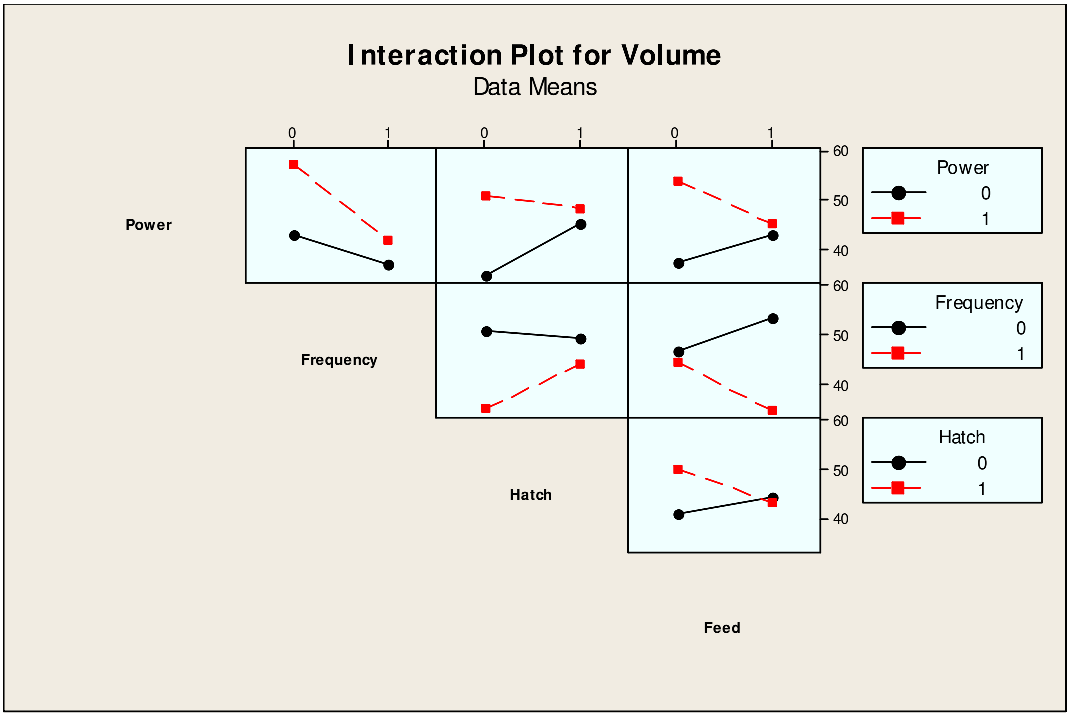


Figure 7: Interactions plot

DOE in the Classroom

WCU's Engineering Technology graduates find themselves predominantly in manufacturing positions, so the exposure to Six Sigma tools proves to be vital. The senior-level Advanced Quality Systems course introduces design of experiments to the ET students. The course does not have an accompanying laboratory, so the students are typically dealing with simulated or archival data. This DOE provides real data for the students, some of whom use the Oxford Laser for independent projects. Although a formal lab is not in place, the development of this DOE allows students a simple tool for running the experiment as a class exercise. Real data illustrate the power of DOE much better than textbook examples or simulated data, as demonstrated by repeated student comments on course evaluations.

Lessons Learned

The use of DOE (design of experiments) is powerful means by which significant input variables can be identified. While this DOE showed no significant input factors as tested, it is apparent that two factors in particular, power and frequency, are on the verge of proving to be statistically significant. Their low and high levels, as specified earlier in this paper, were chosen as a result of previous experience with the machine and based on manufacturer recommendations. If these levels are adjusted slightly, it is very possible that these factors will show a statistical significance.

In the classroom, the use of a real-life DOE helps to reinforce the power of the tool. It should be noted that DOE is used to identify factors that are statistically significant, as well as those that are not. Students seem to appreciate this fact when they see the data presented with a physical part as well.

Conclusion and Further Recommendations

While this DOE did not identify any statistically significant factors, it is anticipated that further investigation will yield such input variables. It is recommended that this DOE is repeated with a larger variation in the levels of the input variables, as well as a possible mid-point, which was alluded to earlier in this paper. The eventual goal of this phase of the research is to take the DOE results and expand them into a regression analysis. Regression will provide the means by which those input variables can be altered to achieve a particular volumetric removal. As experience is gained on this front, the same concept can be extended to controlling surface finish on the machined features. Additionally, this DOE will be developed into a DOE lab for the senior ET students taking the Advanced Quality Systems course. These accomplishments will provide a powerful ability to use the Oxford Laser micro-machining center to machine high-precision micron-level features, while demonstrating to students the use of DOE in a hands-on situation.

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