AC 2007-2776: INTEGRATING LASER MACHINING APPLICATIONS INTO A QUALITY COURSE FOR ENGINEERING TECHNOLOGY STUDENTS

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Integrating Laser Machining Applications into a Quality Course for Engineering Technology Students

Abstract

The graduates of Western Carolina University's Engineering Technology program find themselves in fields that increasingly require that they improve both their hard and soft skills. The recent acquisition of a high-precision, dual-wavelength, five-axis laser machining center from Oxford Lasers in Oxford, England has provided those Engineering Technology students the opportunity to learn and practice high-tech skills related to laser machining, part marking, data matrices, and computer-aided design and manufacturing. Additionally, the data from this multifaceted machine can be used to develop soft skills that are transferable across industrial fields, such as those practiced in the six sigma quality methodology. The results presented in this paper show some of the capabilities of this machine, as well as two DOEs (design of experiments). The DOEs illustrate the relationship between data matrix quality (2-D barcode) and process input parameters, namely pen style, power, hatch, and frequency. Interactions also show a significant effect on the quality of the data matrix.

Introduction

Western Carolina University (WCU) is a comprehensive state university situated in the mountains of western North Carolina with approximately 8,900 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 western North Carolina¹, 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 (Computer-Aided Design & Manufacturing), 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 classroom².

Presently, the Engineering Technology curriculum offers one undergraduate course, Quality Systems, and one graduate course, Quality Assurance, in the area of quality. Based on input from the industrial advisory committee, there are plans to add a second undergraduate course in quality to provide more of those industry-sought six sigma skills. The emphasis on the existing undergraduate course is the application of statistical fundamentals to basic quality tools, such as statistical process control (SPC), gage repeatability and reproducibility (GR&R), and sampling. The graduate course covers a wide array of six sigma tools, such as the DMAIC methodology (Define-Measure-Analyze-Improve-Control), design of experiments (DOE), regression analysis, quality function deployment (QFD), failure modes and effects analysis (FMEA), and mistake proofing. The intent of the proposed new undergraduate course is to introduce some of the six sigma tools that are not covered in the introductory quality course, most notably DOE and regression.

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[®]).

During the Fall 2006 semester, the ET program introduced another state-of-the-art machine to its laboratories with the arrival of the Oxford Laser Micro-Machining and Part Marking System³. In addition to giving students exposure to cutting-edge machining technology, this system provides an outstanding opportunity to reinforce classroom topics, as this paper details.

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

Some of the laser's important features include⁴:

- The laser is a diode-pumped solid state laser meaning that it uses a solid medium that is solid, rather than a gas, such as CO₂.
- 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, allowing for much higher-speed machining.
- The beam can be focused to a spot size adjustable between 6 and 24 microns (μ m) with CNC axis resolution at 0.1 μ m. This provides the capability of micron-level high-precision machining. A human hair is typically on the order of 50 μ m 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 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.
- The enclosed system also means that it 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, conforming to ISO 15415 standards. An additional camera is dedicated to reading data matrices, generated 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 new machine have been to explore its part-marking capabilities. This includes part identification, serialization, data encoding, etc.—essentially any markings that go directly on a component. Anodized aluminum coupons were machined, using the galvo feature, producing the features inside the 49 x 49-mm box, shown in Figure 2.



Figure 2: Coupon machined on Oxford Laser

Shown inside the box are simple text, a data matrix, and a CAD-imported image (Engineering & Technology). When decoded, the data matrix reads "MANUFACTURED USING THE LASER MICRO MACHINING CENTER IN THE ENGINEERING TECHNOLOGY DEPARTMENT AT WESTERN CAROLINA UNIVERSITY" and measures 6 by 6 mm. The dotted line box is actually the text "WESTERN CAROLINA UNIVERSITY" repeated over and over, as shown in Figure 3, under a Nikon SMZ 1500 optical microscope.



Figure 3: Optical microscope view of text lining

The period in the text, following the letter t in Figure 3 was examined on an ADE Phase Shift MicroXAM surface profiling interferometer. The resulting image, shown in Figure 4 was analyzed to show that the diameter of the "period" is 524 μ m with individual lines within the circle measuring 34.4 μ m each. The spacing between those lines is called the hatch spacing, and in this case, run only in the x-direction. This feature is discussed later in this paper, as part of the DOE.



Figure 4: The period between the *t* and *w* in Figure 3

This single coupon begins to show some of the precision the Oxford Laser can accomplish. One of the challenges in exploring the full capabilities of this machine is to find the optimum settings for each application—material, marking contrast, etc. As shown in Figure 2, the data matrix (2-D barcode) is marked more heavily than the text surrounding it, resulting in a greater contrast between the data matrix and the black anodized aluminum coupon. This was not a machining anomaly, but rather a result of different machining parameter settings for each feature. The exploration of these settings is discussed in the following section.

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 recently⁵. New software programs allow the user to deal with many input variables, depending on the particular experiment.

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 $(x_1, x_2, x_3, \text{etc.})$ are varied discretely. In other words those inputs are given a high and a low value (sometimes a middle value is used, as well). 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 variability⁶.

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 commotion. 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 Data Matrix

In this paper, two different four-factor DOEs were explored. The intent of the DOE was to determine which factors had the greatest effect on the quality of a data matrix generated on the laser and read under its barcode-reading camera. Both DOEs used the same output variable—a composite score of the overall quality of the data matrix. According to the ISO 15415 Standard⁷, each of the data matrices was evaluated for the four characteristics below:

- Axial non-uniformity
- Decode
- Print growth
- Symbol contrast

The Oxford Laser's barcode camera read and interpreted each data matrix, assigning a letter grade to each of the categories above, in accordance with the standard. For this DOE, each letter grade was converted to a numerical equivalent as follows:

$$A = 5$$
$$B = 4$$

C = 3D = 2F = 1Fail = 0

An average was taken for the four characteristics, yielding a single numerical output value for a given data matrix—the output y. Each combination of inputs was run three times, yielding three replicates, which were averaged. The four input factors differed for the two DOEs, which were labeled DOE-A and DOE-B, as detailed below:

DOE-A

The first DOE was a full factorial design, using the following four factors:

<u>Variable</u>	Low	<u>High</u>
$x_0 =$ Hatch Spacing	-1 = 0.003 mm	1 = 0.006 mm
$x_1 = Power$	-1 = 85 %	1 = 95 %
x_2 = Distance From Center	-1 = 0 mm	1 = 20 mm
$x_3 = LED$ Intensity	-1 = 130	1 = 160

Hatch spacing is the distance between lines when the laser fills in a space that has been outlined, such as the dot shown earlier (see Figure 4). In the DOE, the hatching is used for both the vertical and horizontal directions at the same spacing. The power is a percentage of full power with 85 to 95% covering the majority of the range recommended by the manufacturer. Distance from center is the x-distance that the data matrix lies from the center of the galvo workspace; the *low* setting is directly in the center and the *high* setting is 20 mm to the right of center. Finally, LED intensity is a setting on the camera that reads the barcode with 130 being on the low end of the recommended range and 160 on the upper end.

The following machine parameters remained constant throughout this DOE:

- Coupon Type: Black anodized aluminum at .47 mm thick
- Barcode Size: 1mm x 1mm
- Barcode Text: OXFORD LASERS
- Laser Beam: 266 nm
- Foreground on barcode camera: White
- Beam movement: Galvo
- Pen style: 1 (100 mm/s)
- Hatches used: 1 (Horizontal) and 2 (Vertical)
- Distance from center movement: X axis only
- Fluorescent lights inside laser: On
- Laser door: Closed during decoding
- Focus height: -10.75 mm from top of table
- Number of times pressing the decode button per barcode: 3
- Direction of scan (Red Arrow): right to left
- Frequency: 20,000 Hz

A sample coupon for DOE-A is shown in Figure 5. Twelve data matrices are shown; the first three are replicates for the first combination; the next three are for the second combination; and so forth. To achieve the three replicates with 16 standard orders (unique combinations) it was necessary to generate 48 individual data matrices, which were burned onto four aluminum coupons similar to that shown in Figure 5.



Figure 5: Coupon for DOE-A with 1 x 1 mm data matrices

The raw data for this DOE were collected and loaded into Table 1 with the average of the three replicates shown in the far right column.

Table 1: DOE-A data

Std Order	Run Order	Order	(3, LED	2, Ctr Dist	(1, Power	(0, Hatch	v1	v2	v3	v avg
2	1	2	1	-1	-1	-1	4	4	3.75	3.92
11	2	11	-1	1	-1	1	4.75	5	4.75	4.83
14	3	14	1	-1	1	1	3.75	3.75	3.75	3.75
3	4	3	-1	1	-1	-1	4.75	5	5	4.92
6	5	6	1	-1	1	-1	0	0	0	0.00
12	6	12	1	1	-1	1	4.5	4	4.5	4.33
16	7	16	1	1	1	1	3.75	1	4	2.92
9	8	9	-1	-1	-1	1	4.75	5	5	4.92
4	9	4	1	1	-1	-1	4	4.5	4.5	4.33
5	10	5	-1	-1	1	-1	1	1	1	1.00
8	11	8	1	1	1	-1	1	0	0	0.33
10	12	10	1	-1	-1	1	3.75	3.75	3.75	3.75
7	13	7	-1	1	1	-1	1	1	1	1.00
15	14	15	-1	1	1	1	4	4	4.25	4.08
1	15	1	-1	-1	-1	-1	4.75	4.5	4.75	4.67
13	16	13	-1	-1	1	1	4.25	4.25	4.25	4.25

The data in the y_avg column were then loaded into Minitab (version 14) to determine which factors and/or interactions had the greatest effect on the output y, which is ideally equal to 5.0, indicating a perfect data matrix. From the data, the main effects plot shown in Figure 6 is developed. The key to interpreting the main effects plot is to find the variable whose line has the greatest slope. In this case the Power (x₁) factor had the greatest effect on the data matrix quality with the low power setting being the best setting of the two. Hatch spacing (x₀) had the next most effect, followed by LED intensity (x₃). Distance from center (x₂) had virtually no effect, and any slope was likely just process variation.



Figure 6: Main effects plot for DOE-A

The next step in the DOE process was to look at any interactions that might exist. Again, Minitab V14 was used to generate the interactions plot shown in Figure 7. The series of graphs can be used easiest by noting that pairs of lines that are parallel or close to parallel have little to no interaction between the corresponding factors. So for the case of Power (x_1) and LED intensity (x_3) , although there is a noticeable slope, the two lines are parallel, and thus there is no interaction between the two. There is a difference in slope of the two lines for the interaction plot between Power (x_1) and Hatch spacing (x_0) . The result of this interaction is that high power and small hatch spacing produces a low quality data matrix, while other combinations generate good matrices.



Figure 7: Interactions plot for DOE-A

DOE-B

The second DOE was a also full factorial design, using the following four factors:

<u>Variable</u>	Low	<u>High</u>
$x_0 = Power$	-1 = 83 %	1 = 93
$x_1 = Pen Style$	-1 = 2 (50.8 mm/s)	1 = 3 (127 mm/s)
x_2 = Frequency (Rep Rate)	-1 = 15,000 Hz	1 = 25,000 Hz
$x_3 = LED$ Intensity	-1 = 130	1 = 160

Similar to the case in DOE-A, the power and LED intensity were factors for the second DOE. The other two factors were Pen style (x_1) and Frequency (x_2) . The pen style is essentially the linear speed at which the laser beam moves along the surface of the workpiece with 50.8 mm/s as the *low* setting and 127 mm/s the *high* value. The frequency is the rate at which the laser pulses—15 kHz is the *low* and 25 kHz the *high* setting.

The following machine parameters remained constant throughout this DOE:

- Coupon Type: Black anodized aluminum at .47 mm thick
- Barcode Size: 1mm x 1mm
- Barcode Text: OXFORD LASERS
- Laser Beam: 266 nm
- Foreground on barcode camera: White
- Beam Movement: Galvo
- Hatches used: 1 (Horizontal) and 2 (Vertical)
- Fluorescent lights inside laser: On
- Laser door: Closed during decoding
- Hatch Spacing for both hatches: 0.005 mm

- Number of times pressing the decode button per barcode: 3
- Direction of scan (Red Arrow): Right to left
- Distance from center: 0 mm

As with the first DOE, the data for DOE-B were collected and loaded into Table 2; the average of the three replicates was calculated and loaded into the column labeled y_avg .

Table 2: DOE-B data

Std Order	Run Order	Order	¢3, LED	κ2, Freq	κ1, Pen	κ0, Power	v1	v2	v3	y avg
2	1	2	1	-1	-1	-1	1	1	1	1.00
11	2	11	-1	1	-1	1	0	0	0	0.00
14	3	14	1	-1	1	1	4	3.75	3.75	3.83
3	4	3	-1	1	-1	-1	4.5	4.5	4.5	4.50
6	5	6	1	-1	1	-1	4.75	4.5	4.75	4.67
12	6	12	1	1	-1	1	0	0	0	0.00
16	7	16	1	1	1	1	4.25	4.5	4.5	4.42
9	8	9	-1	-1	-1	1	0	0	0	0.00
4	9	4	1	1	-1	-1	4.5	4.5	4.5	4.50
5	10	5	-1	-1	1	-1	4	4	4	4.00
8	11	8	1	1	1	-1	0	0	0	0.00
10	12	10	1	-1	-1	1	0	0	0	0.00
7	13	7	-1	1	1	-1	0	1	0	0.33
15	14	15	-1	1	1	1	4.75	4.75	4.75	4.75
1	15	1	-1	-1	-1	-1	1	1	1	1.00
13	16	13	-1	-1	1	1	4.5	1	4.5	3.33

The *y_avg* data were loaded into Minitab V14 and processed to arrive at the main effects plots shown in Figure 8. The factors that had little effect on the output (data matrix quality) were LED intensity (x_3) and Frequency (x_2) , as shown by their negligible slope. Pen style (x_1) had a major effect on the output, while Power (x_0) had a secondary effect by itself.



Figure 8: Main effects plot for DOE-B

The interaction plots proved to be a bit more interesting than in DOE-A. Frequency (x_2) and Power (x_0) had a minor interaction effect, but more dramatic were the interaction between Pen style (x_1) and Frequency (x_2) and between Pen style (x_1) and Power (x_0) . Although Frequency was not significant by itself, it had an interaction effect when coupled with Pen Style—the faster pen style with the lower frequency produced the better data matrices. The interaction between Pen and Power produced the better data matrices when the faster pen style and higher power. This last interaction runs counter to the finding in the main effects, where the lower power produced higher quality data matrices, illustrating the fact that interactions are important to consider when conducting a DOE.



Figure 9: Interactions plot for DOE-B

Lessons Learned

Several key lessons were learned as a result of the DOEs presented in this paper—lessons that are related to DOE generally and to the laser machining center specifically. The power of fractional factorial design allows the experimenter to increase the input variable count without going to the expense of significantly more experimental runs. In these two DOEs there were a total of six unique input factors with two being common to both DOEs—*LED intensity* and *power*. As noted previously, a four-factor full-factorial DOE with three replicates requires 48 experimental runs. Combined, the two DOEs needed 96 individual data matrices to be machined. The down side to running two separate DOEs is that interactions could not be detected for factors that were not common to both experiments, such as *hatch spacing* (DOE-A) and *frequency* (DOE-B). A six-factor half-factorial design would have required the same number of experimental runs (2^6 =64 times 3 replicates = 192 times the $\frac{1}{2}$ -factorial = 96), and would have detected lower-order interactions between factors.

Another general DOE lesson learned, or at least reiterated, is the ability to perform a DOE on a variable that is not typically considered a continuous variable. The data matrix itself has no numerical value to use in the analysis, but by converting its quality scores to an aggregate mark, it is converted to a continuous variable that can be analyzed using DOE techniques.

Through these two DOEs, several lessons were learned relative to the Oxford Laser micromachining center's capabilities. The 1-mm square matrix proved to be rather small for initial efforts in part marking. Achieving a high-quality data matrix was challenging for the small matrix, but a larger matrix tended to generate better quality scores. The data matrix size can be used as a factor in a future DOE.

Another valuable lesson involved the *distance from center* factor explored in DOE-A. With early machining efforts on the Oxford Laser, it was assumed that the quality of the laser etching decreased as the etching moved away from the center of the workspace. This assumption is the reason that this was chosen as a factor in the DOE. As it turns out, the *distance from center* has no effect on the quality of the data matrix, as shown in the main effects plot of Figure 6. Discussion with tech support at Oxford Laser confirmed this fact, as the galvo action eliminates any variation in quality, based on deviation from the center of the workspace. Using hard data, the DOE objectively proved the previous assumption incorrect, and future experimentation will not include *distance from center* as an input.

Conclusion and Further Recommendations

The Oxford Laser Micro-Machining and Part Marking System has proven to be an extremely precise machine to add to the already ample list of facilities available to the Engineering Technology students at Western Carolina University. The laser has already provided valuable instructional information in the form of these two DOEs for the quality classes at WCU. It can also prove useful in demonstrating statistical process control (SPC), using its barcode reading facility, as well as its high precision capabilities. The laser also has innumerable applications from part marking (serialization, data recording, etc.) to micro-device manufacturing for industries such as healthcare.

The two DOEs that were performed and reported in this paper present a stepping off point to pursue the next data matrix DOE. Due to a hardware issue (damaged PC motherboard), this next step could not be completed and presented here. What is evident is that a single DOE should be conducted to investigate the main effects and interactions of pen style, power, hatch, and frequency. As the students and faculty more fully learn the capabilities of the Oxford Laser, there will likely be additional factors to consider, such as matrix size, possibly necessitating a fractional factorial design.

One of the most important instructional points from this DOE approach is that output variables beyond the traditional hole diameter and component length can be analyzed. Six sigma principles, such as DOE, can be applied to a broad array of fields, parts, and processes. Dimensional values will continue to be measured, but now fields such as sales, marketing, and business operations will join the quality movement.

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