Six Sigma-based Quality Control Laboratory for Engineering and Technology Education Innovation

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Abstract

The use of modern sensors and data-acquisition instrumentation for monitoring and control-manufacturing processes was implemented into laboratory practices in undergraduate classes on gauging, measurement, inspection, diagnostic systems, and quality control at Drexel University. The network hardware and software components were integrated with quality methodologies to achieve maximum effectiveness in teaching E-quality concepts in various courses, including MET 204 Applied Quality Control, MET 310 Advanced Robotics and Mechatronics, and INDE 470 Engineering Quality Methods. In INDE 470, laser machining of plastics (acrylics) for applications to microfluidic ‘lab-on-a-chip’ devices offered an instructive and practical case study to teach Six Sigma Quality Assurance concepts and methods to Engineering Technology (ET) students. A 10-week upper-level undergraduate course was developed that included a classroom component with lectures on Six Sigma principles and methods, combined with hands-on laboratory sessions that included product manufacture (laser machining of acrylic) and quality assessment measurements to support experimental design and data analysis in a Six Sigma framework. Students made various measurements of laser-machined parts using a coordinate measuring machine (CMM) and machine vision (i.e., a CCD camera with image-processing software). Students then analyzed measurement data to compare measurement techniques (Gage R&R), establish part variations, correlate quality metrics with laser processing parameters, and optimize the laser-machining process using Design of Experiments.

Background

Undergraduate Engineering Technology (ET) curricula in Mechanical Engineering, and Industrial or Manufacturing Engineering have traditionally included courses in Quality Methods and Statistical Process Control. For example, the Drexel ET program features several courses in Statistical Process Control and Quality Engineering, including an upper-level course, INDE 470 “Engineering Quality Methods.” The course syllabus was comprised of topics on statistical distributions, probability plots, hypothesis testing, regression and correlation, control charts, ANOVA, and Process Measurement and System Capability Analysis. The INDE 470 course syllabus was modified to introduce students to Six Sigma concepts and teach Engineering Quality with emphasis on Six Sigma methodologies. Six Sigma is a data-driven, quality assurance and process-improvement system to identify root causes and solve quality-related problems in manufacturing using statistical analyses and other techniques. Six Sigma provides a ‘toolbox’ of statistical methods and other techniques that can be systematically applied to eliminate or drastically reduce defects and enhance quality (reduce variations) in manufacturing and service operations.

Six Sigma was pioneered by Motorola in the 1980s and is now well-established in many industries. Companies utilizing Six Sigma include Agilent, Boeing, DuPont, Ford, General Dynamics, General Electric, and Honeywell. Six Sigma is also increasingly employed in-service sector industries including banking and finance, healthcare and education [1-3]. There is considerable literature on Six Sigma including a large number of books suitable as texts or supplemental readings for undergraduate courses offered in Bachelors of Engineering or Engineering Technology programs. For the INDE 470 class, Six Sigma reading materials were selected from sources listed in the references. Six Sigma courses and training programs are increasing in popularity. For example, Drexel University offers Six Sigma classes to industry professionals as continuing education courses in a ten-week all-day Saturday format.

There are also numerous consulting firms that market on-site Six Sigma programs to industry, as well as on-line courses offered by various academic institutions. Students in these courses can gain credentials through Six Sigma Certification. Despite its prevalence in industry, Six Sigma is not commonly encountered in undergraduate engineering and technology curricula. Nevertheless, it should be noted that many components of the Six Sigma approach are standard statistical techniques taught in traditional engineering courses. Therefore, the topical coverage of a Six Sigma course need not deviate from those typically covered in the conventional engineering curricula. Instead, the presentation of topics, and in particular their integration into a Six Sigma program, are tailored according to the standard format of Six Sigma courses offered to industry. In Engineering Technology programs, the emphasis is on hands-on problem solving. Accordingly, the authors developed a laboratory case study where students made measurements, and collected and analyzed data using Six Sigma methods [4].

The Six Sigma approach provides a programmed structure for rational implementation of statistical methods in order to 1) identify value-added attributes and features according to customer preferences, 2) validate or discover key process variables that impact these value-added features, 3) estimate capabilities in achieving quality objectives, and 4) to provide methods that establish, improve, and control processes in order to achieve and maintain quality objectives. Specifically, a project to improve quality of a particular product or process proceeds through five stages termed Define, Measure, Analyze, Improve, and Control (DMAIC) [5], [6]. Various quality and statistical methods are applied at each stage (see Table 1). The initial Define stage defines the problem by identifying features or aspects in a product that provide value to the customer, and the key process variables or design features that impact these value-added aspects of the product. A common method to achieve the Quality Function Deployment (QFD) is the House of Quality diagram (Figure 1), which maps customer needs and priorities onto relevant design features and process variables, and can be used to prioritize design and processing variables and delineate correlations, interactions, and conflicts between variables.

Table 1. Stages of the Six Sigma program

Six Sigma Methods		
1. Define	2. Measure	3. Analyze
Benchmarking, PMEA, IPO Diagram, Kano's Model, Knowledge Based Mgt, Project Charter, SIPOC Model, Quality Function Deployment, Voice of Customer, Task Appraisal/Task Summary, Value Stream Mapping.	Confidence Intervals, Measurement System Analysis, Nominal Group Technique, Pairwise Ranking, Physical Process Flow, Process Capability Analysis, Process Observation, Time Value Map, Value Stream Mapping, Waste Analysis, Gage R&R	Affinity Diagram, Brainstorming, Cause & Effect Diagram, e-test, F-test, Fault Tree Analysis, FMEA Histogram, Historical Data analysis, Pareto Chart, Reality, Regression Analysis, Scatter Diagram, t-test, Thermatic Content Analysis, Turkey End Count Test, 5 Whys
4. Improve	5. Control	
DFSS, DOE, Kanban, Mistaken Proofing, PF/CE/CNX/SOP, Standard Work, Takt Time, Theory of Constraints, Total Productive Maintenance, Visual Management, Workcell Design, 5S Workplace Organization	Control Charts, Control Plan, Reaction Plan, Run Charts, Standard Operating Procedures	

Six Sigma Case Study

In industrial settings, participants in a Six Sigma program can select actual quality problems from their work as case studies on implementing Six Sigma methods. For undergraduate students who likely are not employed in a situation that readily presents good problems for application of Six Sigma methods, a simulated case study is more appropriate [7-11].

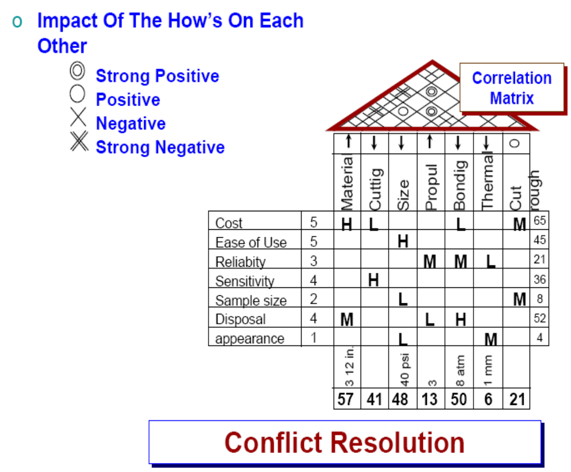


Figure 1. House of Quality in Design Stage of Six Sigma Case Study of laser machined workpieces

Figure 1 shows an example of a completed House of Quality analysis for the present case study. In the following Measure stage, various performance metrics are assessed, and interpreted in the subsequent Analyze stage. During the Improve or Implement Stage, the process can be optimized using Design of Experiments and other techniques. In the Control stage, methods to sustain quality improvements gained in the previous stages are formulated and implemented.

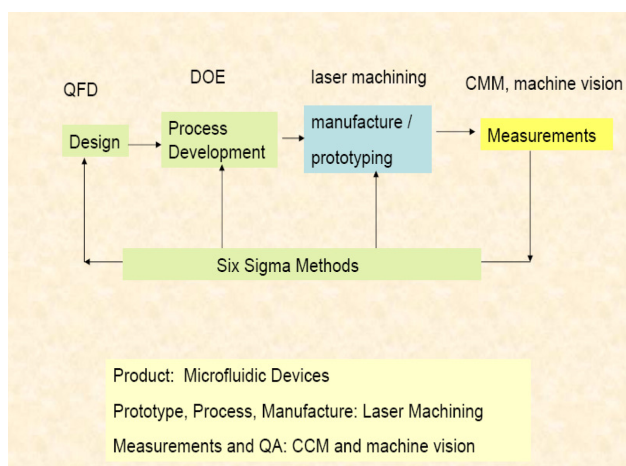


Figure 2. Overview of Six Sigma Case Study

An overview of the Six Sigma project for the Case Study described here is shown in Figure 2. The product of interest is a plastic lab-on-a-chip made by a laser-machining process which can be optimized by Design of Experiments and assessed by CMM and machine-vision measurements of laser-machined parts. The measurement data were analyzed using

Six Sigma methodologies. Figure 3 shows a flow chart for measurements in a scheme to compare the usefulness of CMM versus machine-vision assessment of product quality. CMM measurements are considered more accurate, but more tedious (requiring much handling) and time consuming. Machine-vision measurements are faster and can be more easily automated. However, machine-vision measurements are not as accurate. Therefore, one objective of this case study was to correlate and compare data by these two measurement techniques [12], [13].

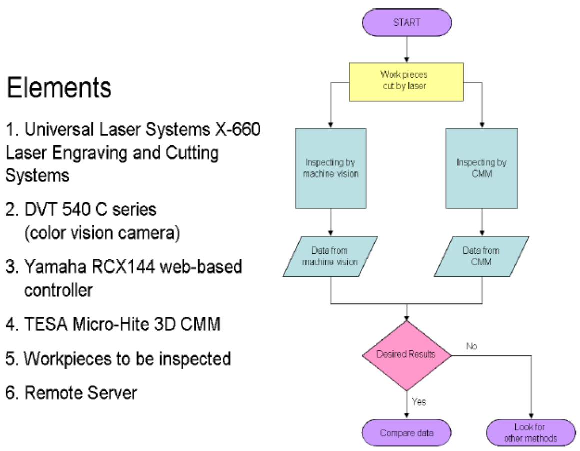


Figure 3. Flow-chart for measurements in laboratory sessions

Laser Machining of Acrylic Plastic

Laser machining can be used for both rapid prototyping and production. The relevant laser-machining parameters are the scanning speed and power of the laser.

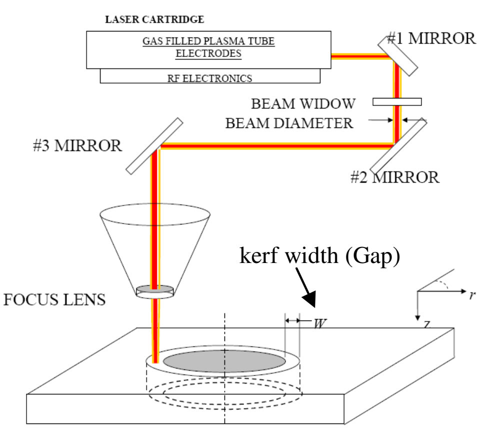


Figure 4. Schematic of Laser Cutting Process

In this study, the authors used laser machining to cut acrylic plastic sheets for application to microfluidic devices. Acrylic plastic is clear or contains coloring agents and, therefore, the opacity of the plastic stock was also a process variable. Laser machining was performed in a Universal Laser Systems (Tempe Arizona) Model X-660. Workpiece patterns drawn in AutoCAD™ can be directly downloaded into the Laser Machining system. Acrylic (PMMA) sheets ranging from 0.1mm to 1mm in thickness were used as stock. Microfluidic chips can be fabricated as a composite structure. Figure 4 shows a schematic of the laser-cutting operation.

Acrylic (plastic) sheets approximately 6mm thick were machined with an array of circular and rectangular holes using the Universal Laser Systems Model X-660. The circular hole diameter was approximately 20mm, and the approximate square rectangular hole had a width of about 18mm. An AutoCAD™ drawing was used to design the hole pattern. Each circular or rectangular hole of an array was nominally the same. The test patterns are shown in Figure 5.

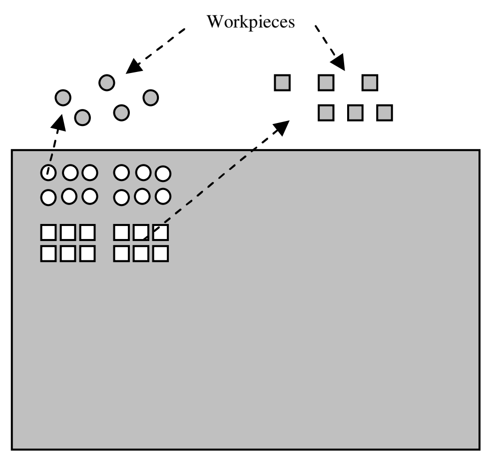


Figure 5. Test patterns and workpieces made by laser cutting on the acrylic sheet

The CO_2 laser has variable power and (travel) speed. It was assumed that the reproducibility, accuracy, and precision of the cut may depend on laser power, travel speed, type of material, and material thickness, among other variables. For each combination of power and speed setting, twelve circular and twelve rectangular holes were cut in a sheet. The acrylic sheet was of two types: clear and black. Normally, the color would not be a significant factor in machining material, however, it was conjectured that the optical absorption of laser light might differ between the two types of acrylic and, therefore, the quality of the cut might depend on the color of the material. Table 2 summarizes the laser-cutting data.

Table 2. Summary of Laser Cutting Parameters

Set	Material	Power (Watt)	Speed (mm/s)
A	Plexiglas MC	60	1.4
B	Plexiglas MC	60	0.7
E	Plexiglas MC	60	0.3
H	Plexiglas MC	45	0.3
I	Plexiglas MC	36	0.3

Calibration Algorithm

To calibrate the machine-vision measurement system, sample data were compared with the standard CMM target. The data were then fit to a line and the equation of the line was stored for later use. To judge the quality of a linear fit without being able to see a graph of the data, an R-Squared (R^2) value was calculated as well. The R^2 value represents the proportion of variation in the response data explained by the predictors. This means that the higher the R^2 value, the greater the chance that the index alone will describe the measured value. Mathematically, the R^2 value is literally the square of the correlation coefficient value R. The correlation coefficient can be derived using the following equation:

$$r_{xy} = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{(n-1)s_x s_y} \tag{1}$$

where the standard deviation of the population is estimated using

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \tag{2}$$

with an average of $\bar{x} = \frac{1}{n}\sum_{i=1}^{n} x_i$, where n is the number of sample data.

The line equation that is required is of the form y = mx + b, where m is the slope and b is the intercept. The slope is found first using $m = r\, S_y/S_x$. The r is the same one that was calculated as the correlation coefficient earlier. The slope is then used in the calculation to find the intercept using $b = \bar{y} - m\bar{x}$. This linear equation works when the measurement value is in bits like the trial or as volts like what was used from this point forward in the study.

Dimensional Measurements of Laser Machined Acrylic Parts

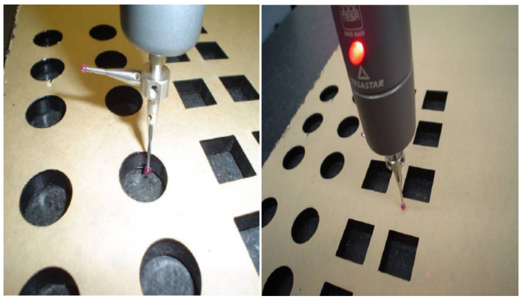
A TESA (Renens, Switzerland) coordinate measurement machine (CMM) was used to dimension the workpiece features. A CMM is an instrument for dimensional measuring. It is a machine that is used to move a measuring probe to obtain the coordinates of points on an object surface. These machines are commonly used to measure the dimensions of target objects. For any machined part, a number of metrics (dimensions, angles, or other geometric features) can be measured as indicators of function, conformance, or quality. For circular holes, the diameter, cylindricity, and roundness are measured. For rectangular holes, two widths, as well as the edge angle are measured.

The use of the CMM for the tasks at hand was demonstrated by the teaching assistant. The students, working in groups, collected data for some assigned subset of the workpieces. Data was entered into an EXCEL spreadsheet for analysis. Figures 6(a) and 6(b) show details of the measurement step with the CMM probe contacting the laser-machined features of the acrylic test piece. Replicate (10X) measures on a single hole to ascertain the variance of the measurement process were made. The variance was denoted as σ^2_{meas}. The variance of measurements for a set of holes in the workpiece, σ^2_{wp} , was then found from the observed variance σ^2_{obs}

$$\sigma^2_{\text{obs}} = \sigma^2_{\text{meas}} + \sigma^2_{\text{wp}} \tag{3}$$

which takes into account the inherent variance of the measurement process.

For several laser settings (power and speed), types of sheet material (clear acrylic, black acrylic, fiberboard), and both sets of holes (rectangular and circular) measurements for at least two metrics (e.g, diameter, roundness, cylindricity, widths, etc.) were made. There were n = 12 data points for each group. In each case, mean and variance were calculated. The data from the class was pooled so that a single common spreadsheet contained data for all the conditions shown in Table 2. The students were asked to solve the following questions and tasks: 1) Determine if the data appear to be consistent with a normal distribution (make a plot or histogram) in the twelve data points in any set of data, 2) Perform an ANOVA to determine if there is any significant difference in the means of measurements for different laser-cutting conditions and materials, 3) Use a *t*-test to test for a significant difference in means between several pairs of groups, 4) Use an *F*-test to test for a significant difference in standard deviations between several groups of measurements, and 5) Interpret data and statistical analyses if the laser power and speed, or material, have any impact on quality (variance).



(a) (b)

Figure 6. Detail view of CMM probing of laser machined acrylic test pieces

Machine-vision Measurement

In addition to the CMM measurements, similar sets of measurements on the same laser-machined test pieces were performed using machine-vision inspection. The machine-vision set-up was comprised of a CCD camera connected to some electronics and a PC with image-processing software (Figure 7). Machine-vision packages for the Cognex DVT 540 computer-vision system were configured as a set of tools for Internet-based inspections and measurements. SoftSensors were the working class inside Smart Image Sensors. Every type of SoftSensor serves a specific purpose, and the combination of the SoftSensor results represent the overall result of the inspection. The machine-vision camera was initially trained to learn the profile and make measurements of a part being tested through the FrameWork software.

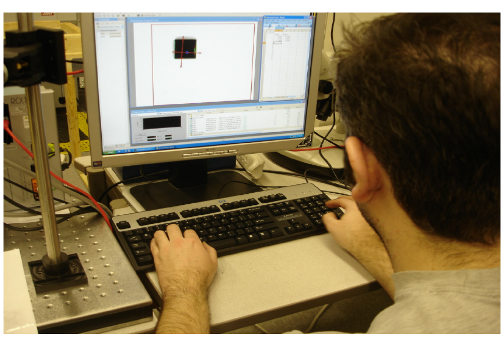


Figure 7. Students capturing images of laser-machined test part features with machine-vision setup

Details of the machine-vision inspection include: 1) machine-vision system = CCD camera + electronics + PC + software, 2) camera: Smart Image sensor model 454C with LED illumination, 3) image-processing software: Intellect, 4) works on contrast (difference in intensities of pixels) in 2-D plane; gray scale 1→ 255 levels, 5. 640 x 480 pixels = 307 K, and 6. 1280 x 1024 pixels = 1.3 million.

For the square test patterns, the probe was moved just below the surface of the acrylic sheet and touched three times on each opposing side of the hole, as shown in Figure 8. For the round test patterns, the probe was moved just below the surface of the acrylic sheet and touched 8 to 10 times outward around the circumference (the blue and red arrows). The data points (diameter and roundness) were displayed and recorded by the CMM.

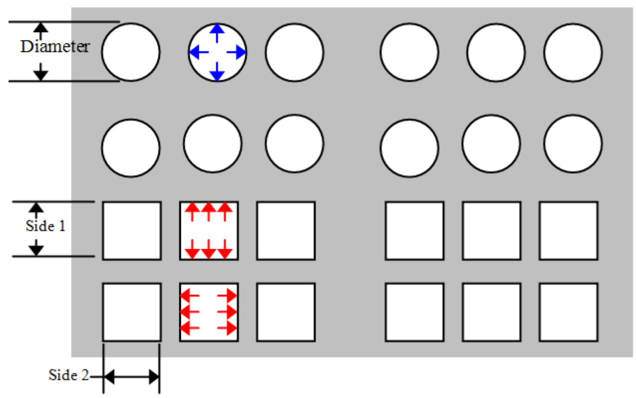


Figure 8. The test pattern measurements method

Figure 9 shows the same test method for the workpieces. However, the CMM probe touched them inward on the rim with the same times and test patterns.

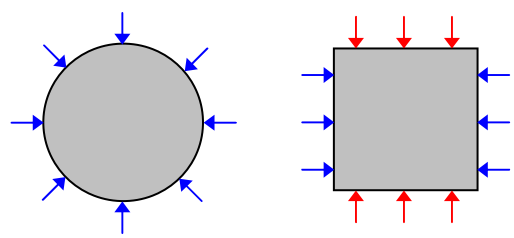
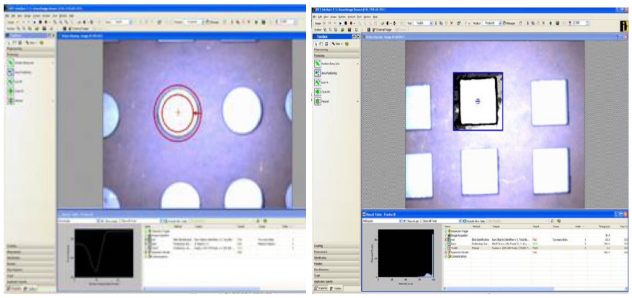


Figure 9. The probe measurement method for workpieces

A number of metrics (dimensions, angles, or other geometric features) can be measured as an indicator of function, conformance or quality. For circular holes, the diameter and roundness can be easily measured by machine vision. For rectangular holes, two widths can be measured by machine vision, as shown in Figure 10. The students, working in groups, collected data for some assigned subset of the workpieces. Data was entered into an EXCEL spreadsheet for analysis.



(a) Circular (b) Rectangular

Figure 10. Image processing of circular and rectangular features to determine geometric parameters of laser-machined part features

Statistical Findings

In the lecture portion of the course, students were instructed in various statistical methods that are commonly employed in Six Sigma. These include binning of data, histograms, probability plots, ANOVA, linear regression, and correlation. All of these analyses can be performed on EXCEL spreadsheets, including graphical presentations of results. Figures 11 and 12 show examples of statistical tests on laser-machined acrylic parts, with relevant details included in the figure captions. These studies show that the characteristics produced by typical CO_2 laser-machining of acrylic sheets are amenable to standard statistical tests used in industry. These statistical analyses shown were made using Microsoft Excel™; however, the laboratory exercises can be incorporated into courses based on other statistical software packages such as MiniTab™.

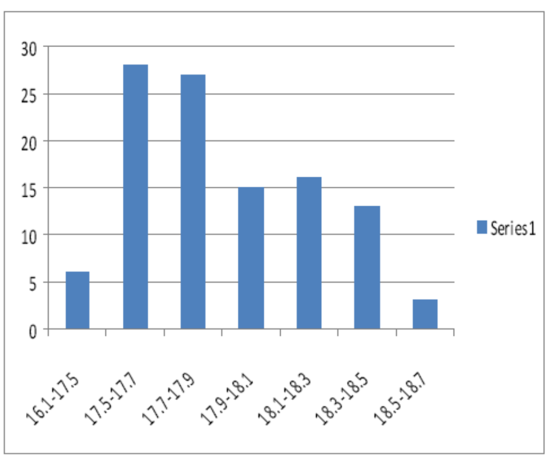


Figure 11. Binning of data for laser-machined holes according to the diameters measured by the CMM

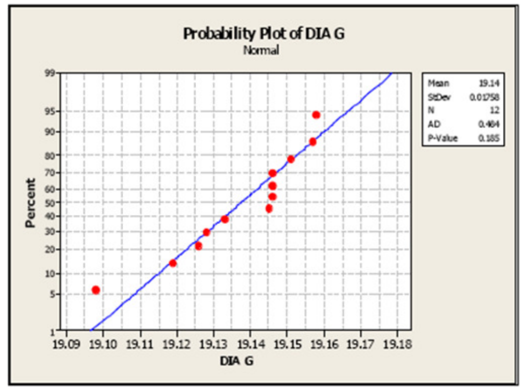


Figure 12. Probability plots for implying the data distribution

Figure 13 shows the distribution on diameters of various laser-machined circular holes. These diameter frequencies were processed by Histogram analysis. The algorithms gave 100% accuracy to detect the diameters of the laser-machined holes and the workpieces. Therefore, the gap between a hole and the cut workpiece from the hole can be calculated.

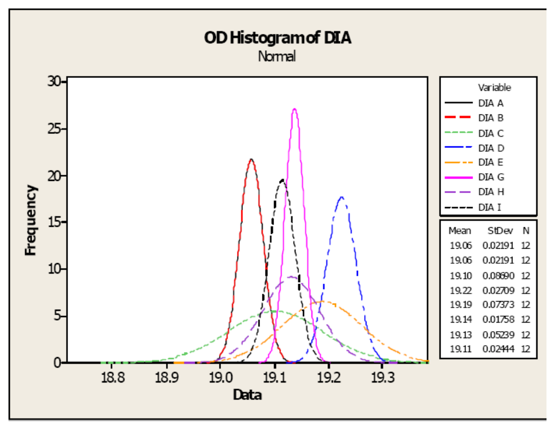


Figure 13. Distribution of data on diameters of various laser-machined circular holes

Table 3 shows how a *t*-test is used to test for a significant difference in means between several pairs of groups. It can be seen that the *t*-test can be used to test for a significant difference in standard deviations between several groups of measurements.

Table 3. CMM: t-Test: Two sample assuming Unequal variances

	A	B
Mean	18.256	17.9707
Variance	0.00036	0.35715
Observation	12	12
Hypothesized Mean Difference	0	
df	11	
tSat	1.65309	
P(T<=t) one-tail	0.06327	

tCritical one-tail	1.79588	
P(T<=t) one-tail	0.12654	
tCritical one-tail	2.20099	
	C	**D**
Mean	18.34842	18.44617
Variance	0.006587	0.002692
Observation	12	12
Hypothesized Mean Difference	0	
df	18	
tSat	-0.534464	
P(T<=t) one-tail	0.001184	
tCritical one-tail	1.734064	
P(T<=t) one-tail	0.002368	
tCritical one-tail	2.100922	
	E	**F**
Mean	19.18858	19.13775
Variance	0.005437	0.000309
Observation	12	12
Hypothesized Mean Difference	0	
df	12	
tSat	2.323091	
P(T<=t) one-tail	0.019275	
tCritical one-tail	1.782288	
P(T<=t) one-tail	0.038551	
tCritical one-tail	2.178813	

Machine-vision Results

To obtain the kerf width of laser cutting by a machine-vision system, the average data of test patterns has to be subtracted from the diameter of the workpieces. Then the kerf width can be obtained by dividing the test-piece gap widths. All the data are shown in Table 4.

Table 4. Results of Set E, H, and I

Power	60		45		36	
no.	Test pattern E Circle	Workpiece E	Test pattern H Circle	Workpiece H	Test pattern I Circle	Workpiece I
1	20.35	19.82	20.056	19.93	19.74	20.2
2	20.32	19.68	19.908	20.28	19.828	20.3
3	20.41	19.78	19.822	20.01	20.24	20.14
4	20.32	19.94	20.054	20.14	19.67	20.26
5	20.63	19.84	20.01	19.96	20.014	20.22
6	20.56	19.88	20.048	20.11	19.95	20.2
7	19.9	19.8	20.064	19.9	19.97	19.5
8	19.68	20.08	19.982	19.67	19.958	19.55
9	19.35	19.84	19.988	19.41	19.976	19.41
10	19.41	19.76	20.05	19.44	19.574	19.27
11	20.1	19.84	20.034	19.3	19.828	19.08
12	19.88	19.74	20.09	19.3	19.94	19.29
Avg	20.076	19.833	20.009	19.788	19.891	19.785
Kerf Width	0.121		0.111		0.053	

Coordinate Measuring Machine (CMM) Results

For CMM measurements, the authors used the same approach as was used with machine vision. By taking the average of the twelve data, the value in each cell can be obtained, as shown in Table 5.

Table 5. Summary results measured by CMM

Feature	Kerf Width Side 1	Kerf Width Side 2	Kerf Width Diameter	Kerf Width Average
A	0.275	0.295	0.275	0.282
B	0.353	0.402	0.376	0.377
E	0.410	0.437	0.429	0.425
H	0.370	0.396	0.362	0.376
I	0.342	0.340	0.330	0.337

For both machine vision and CMM, students made replicate (10X) measurements on a single hole to ascertain the variance of the measurement process. The data from the CMM and machine-vision system were correlated with each other. For a given part feature (e.g, hole) and laser settings (e.g., speed and power)), the measurements from lowest to highest in each set were arranged: one set for the CMM and one set for the machine-vision system, as shown in Figure 14. Then, the correlation coefficient and the best line fit can be found.

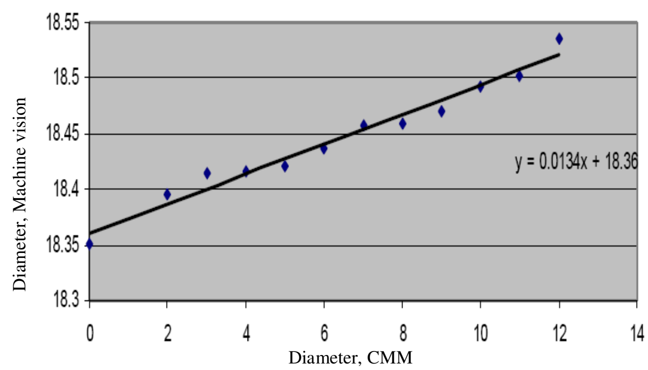


Figure 14. Correlation of diameter values measured by CMM with machine-vision parameters

From Table 4, the relationship between power and the kerf width (gap) can be plotted, as shown in Figure 15. It can be seen that the gap (mm), defined as the diameter difference between the hole diameter and workpiece diameter (measured by CMM), is a function of laser power and speed in Figure 16.

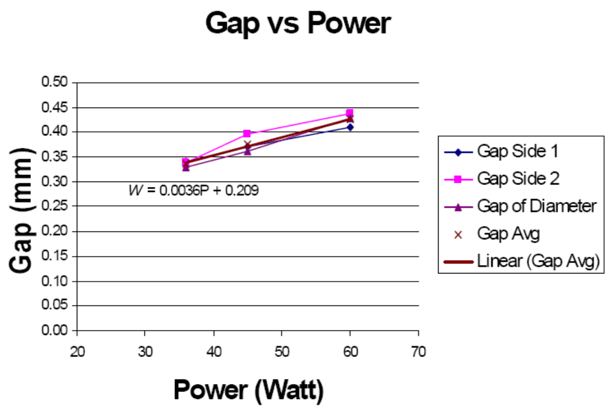


Figure 15. Dependence of the kerf width on the laser output power measured by CMM

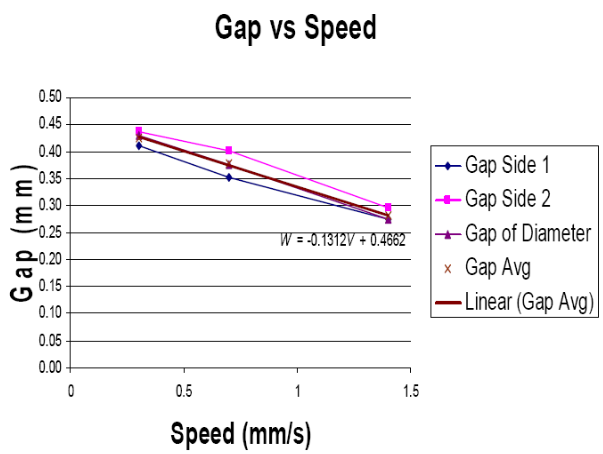


Figure 16. Dependence of the kerf width on the laser cutting speed measured by CMM

Mathematical Relation

From the experiment data collected in this study, when speed equals 0.3mm/s, the results can be plotted, as shown in Figure 15. A linear relationship was found for laser data between 36 and 60 watts. The averaged data of the kerf width, W, was fit to

$$W = 0.0036\ P + 0.209 \qquad (4)$$

where *P* is the power of the laser.

When power equals 60 watts, the relationship between kerf width and speed can be determined (see Figure 16). The data were considered to be linear under the condition that the speed falls between 0.3 and 1.4mm/s. The averaged data shows a linear dependence fit as

$$W = -0.1012\ V + 0.4682 \qquad (5)$$

where *V* is the speed of the laser.

Since the two equations were considered to be linear, a plane was determined by the cross product of these two vectors. Now, equations (4) and (5) can be rewritten into the vector form as [W V P]. Let $\vec{A} = [1\ 0\ -0.0036]$, $\vec{B} = [1\ 0.1012\ 0]$, then $\vec{A} \times \vec{B} = [0.0004\ -0.0036\ 0.1012]$.

Assuming that E is set to the initial conditions: *W* = 0.425mm, *V* = 0.3mm/s, and *P* = 60 watts, then the plane equation can be determined as

$$0.0004\ W - 0.0036\ V + 0.1312\ P = 6.0711 \qquad (6)$$

In this way, a model for the variable setting for this acrylic material can be built by rewriting equation (6) into equation (7)

$$W = 9.0V - 253.0P + 15177.75 \qquad (7)$$

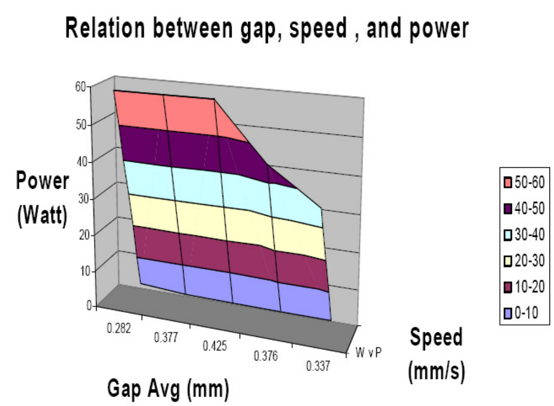


Figure 17. The relationship between kerf width, speed, and power

The dependence of kerf width on laser speed and power for this acrylic material is clear. Furthermore, the relation between kerf width and speed can also be determined from features E, B, and A. Figure 17 shows a Design of Experiments (DOE) case study exploring the correlation of the gap size (indicative of laser kerf) with laser power and cutting speed. Such studies permit students to optimize the process in order to achieve target specifications.

Design of Experiments (DOE)

Students used the Stat-Ease® Design of Experiments (DOE) software package from Stat-Ease, Inc. [14]. A free

45-day trial version was available to all students. The package is well-documented and supported with instructive material. Students found the Stat-Ease package easy to use. For the present case study, a three-variable (laser speed, power, plastic transparency), two-level DOE study was undertaken to suggest subsequent experiments to optimize the laser-machining process.

Discussion and Conclusion

The study of laser-machining of acrylic plastic sheets for application to quality inspection and diagnostics devices provides an instructive case study of Six Sigma concepts and methods. The manufacturing and quality issues are conceptually straightforward, and the laser-machining and CMM or machine-vision inspection laboratories can each be performed in one two-hour laboratory session. Based on student evaluations of the lab, which were completed after each laboratory session, the objectives of the Six Sigma case study were substantially achieved.

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