AC 2009-1858: DEVELOPMENT OF E-QUALITY LABORATORY MODULES FOR USE IN ENGINEERING QUALITY-CONTROL COURSES

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Development of E-Quality Laboratory Modules for Use in Engineering Quality Control Courses

Abstract

Recent results of laboratory and course development under an NSF, CCLI sponsored project, "CCLI Phase II: E-Quality for Manufacturing (EQM) Integrated with Web-enabled Production Systems for Engineering Technology Education" (NSF Award # 0618665) are presented. A multi-disciplinary team of faculty developed lectures and laboratory modules for use in Engineering Quality courses. The use of modern sensors, data acquisition instrumentation for monitoring and control manufacturing processes is implemented into laboratory practices in undergraduate classes on Web-based gauging, measurement, inspection, diagnostic system, and quality control. The network hardware and software components are 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 offers an instructive and practical case study to teach *Six Sigma Quality Assurance* concepts and methods to Applied Engineering Technology (AET) students. A 10-week upper-level undergraduate course was developed that included a classroom component presenting 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. Acrylic sheets can be readily patterned with microfluidic circuits using a commercial CO_2 laser machining system that is representative of typical engineering prototyping and commercial manufacturing. The quality of the laser machining, particularly with regard to reproducibility, can be investigated as a function of laser power and speed, and also as the optical properties of various grades of acrylic stock. Students made various measurements of laser-machined parts using a co-ordinate measuring machine (CMM) and Internet-based 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 curricula in Applied Engineering Technology (AET), Mechanical Engineering, and Industrial or Manufacturing Engineering have traditionally included courses in Quality Methods and Statistical Process Control. For example, the Drexel AET Program features several courses in Statistical Process Control and Quality Engineering, including an upper-level course titled INDE 470 "Engineering Quality Methods". The course syllabus comprises topics on statistical distributions, probability plots, hypothesis testing, regression and correlation, control charts, ANOVA, and Process Measurement and System Capability Analysis. The Winter 2008 INDE 470 course syllabus was modified to introduce 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 a 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 Bachelors of Applied Engineering programs. For the INDE 470 class, Six Sigma reading materials were selected from sources listed in the bibliography. Six Sigma courses and training programs are increasingly popular. 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 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 Applied Engineering Technology programs, the emphasis is on hands-on problem solving. Accordingly, we 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 this so-called Quality Function Deployment (QFD) is the House of Quality diagram 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 Six Sigma program and methods typically used at each stage.

Six Sigma Methods				
1. Define	2. Measure	3. Analyze	4. Improve	5. Control
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	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[7-10].

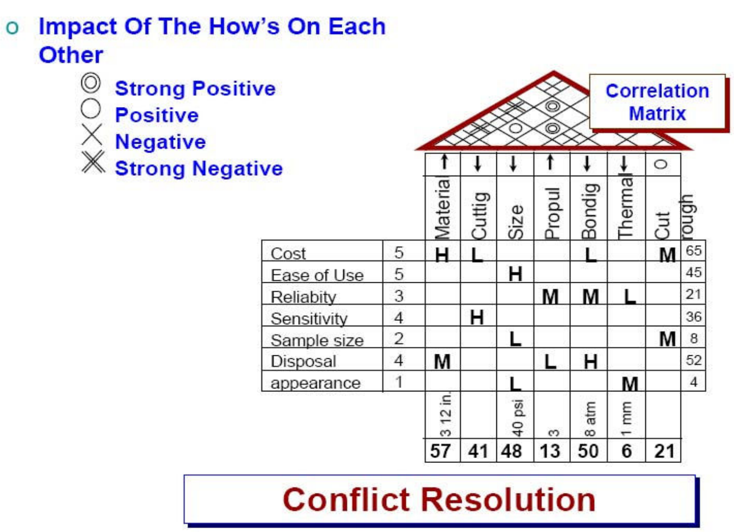


Figure 1: House of Quality in Design Stage of Six Sigma Case Study of laser machined workpieces.

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.

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 is analyzed using Six Sigma methodologies. Figure 3 shows a flow chart for measurements in a scheme to compare the usefulness of CMM vs. 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 is to correlate and compare data by these two measurement techniques.

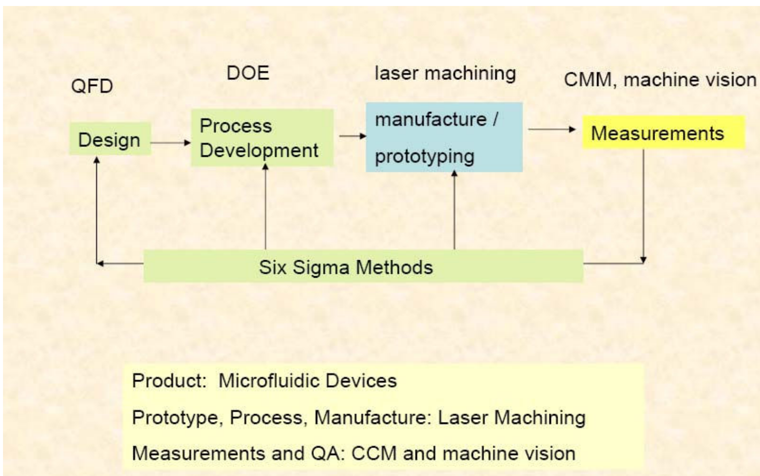


Figure 2: Overview of Six Sigma Case Study

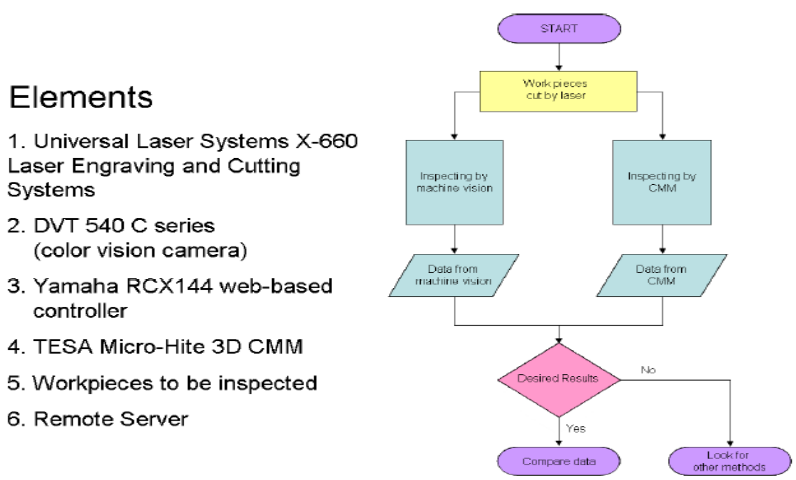


Figure 3: Flow-chart for measurements in laboratory sessions.

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. We 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 0.1 mm to 1 mm 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.

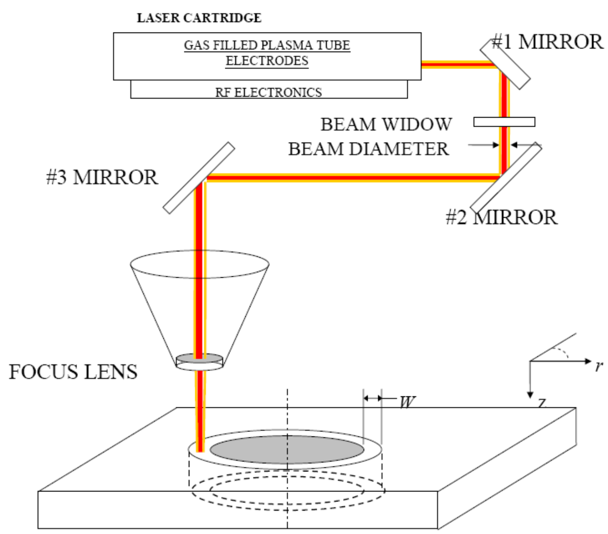


Figure 4: Schematic of Laser Cutting Process.

Acrylic ('plastic') sheets (approx. 6 mm thick) were machined with an array of circular and rectangular holes using the Universal Laser Systems Model X-660. The circular hole diameter is approximately 20 mm, and the approx. square rectangular hole has a width of about 18 mm. An AutoCAD™ drawing is used to design the hole pattern. Each circular or rectangular hole of an array is nominally the same.

The CO_2 laser has variable power and (travel) speed. It is 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 is of two types: clear and black. Normally, the color would not be a significant factor in machining material, however, it is 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 below summarizes the laser cutting data.

Table 2: Summary of Laser Cutting Parameters

Run	Material	Power (%)	Speed (rel)	comment
A	BA	100	0.40	
B	BA	100	0.75	
C	CA	100	0.70	
D	CA	100	0.30	
E	BA	100	0.30	
F*	BA	100	3.00	not cut thru
G	FB	100	0.70	
H	BA	75	0.30	
I	BA	60	0.30	
J*	FB	100	3.00	not cut thru

CA = clear acrylic, BA = black acrylic, FB = fiber board * not cut thru and therefore cannot be used for our analysis.

Dimensional Measurements of Laser Machined Acrylic Parts

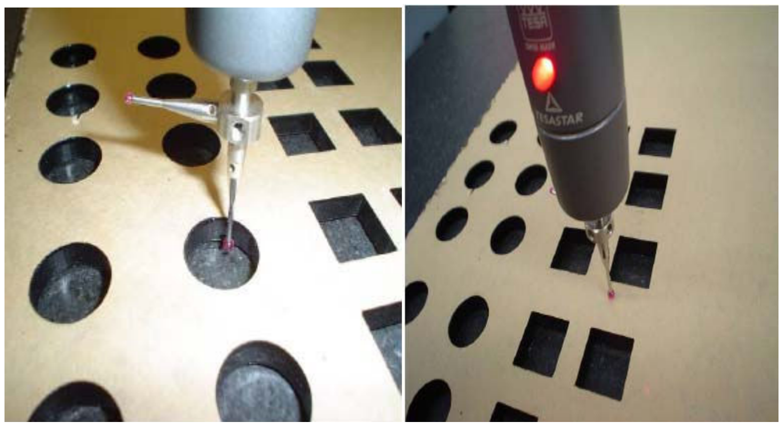
A TESA (Renens, Switzerland) CMM (co-ordinate measurement machine) is used to dimension the workpiece features. A CMM is an instrument for dimensional measuring. It is a machine that is used to move a measuring probe to obtain the coordinates of points on an object surface. These machines are commonly 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 an indicator 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 5a and 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 is denoted as σ^2_{meas}. The variance of measurements for a set of holes in the workpiece σ^2_{wp} is then found from the observed variance σ^2_{obs}

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

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) measure at least two metrics (e.g.., diameter, roundness, cylindricity, widths, etc…). 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 contains data for all the conditions shown in the Table 1. The students were asked to solve the following questions and tasks: 1. Find 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 for between several groups of measurements, and Interpret data and statistical analysis if the laser power and speed, or material, have any impact on quality (variance).



(a) (b)

Figure 5: Detail view of CMM probing of laser machined acrylic test pieces.

Internet-based Machine Vision Measurements

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 is comprised of a CCD camera connected to network electronics and a PC with image processing software (Figure 6). Machine vision packages for the Cognex DVT 540 computer vision system are configured as a set of tools for Internet-based inspections and measurements. SoftSensors are the working class inside Smart Image Sensors. Every type of SoftSensor serves a specific purpose, and the combination of the SoftSensor results represents the overall result of the inspection. The machine vision camera is initially trained to learn the profile and make measurements of a part being tested through the FrameWork software. Details of the machine vision inspection include:

- Machine Vision System = CCD camera + electronics + PC + software
- Camera: Smart Image Sensor Model 454C with LED illumination
- Image processing software: Intellect
- Works on contrast (difference in intensities of pixels) in 2-D plane
- Gray scale 1→ 255 levels
- 640 x 480 pixels = 307 K
- 1280 x 1024 pixels = 1.3 million

For any machined part, 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 7. The students, working in groups, collected data for some assigned subset of the workpieces. Data was entered into an EXCEL spreadsheet for analysis.

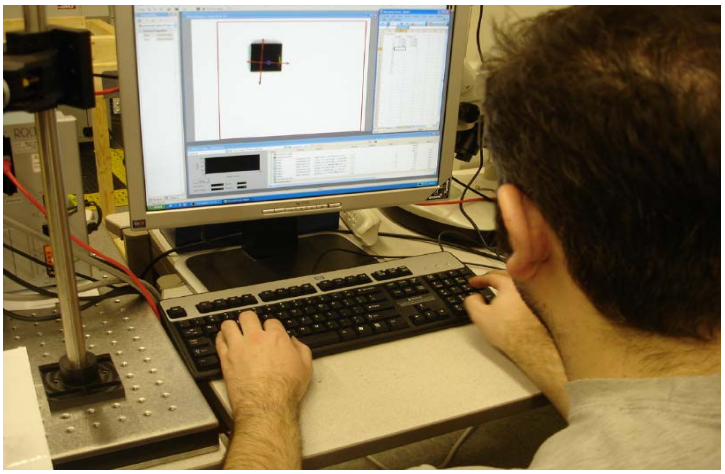


Figure 6: Students capturing images of laser-machined test part features with Internet-based machine vision set up.

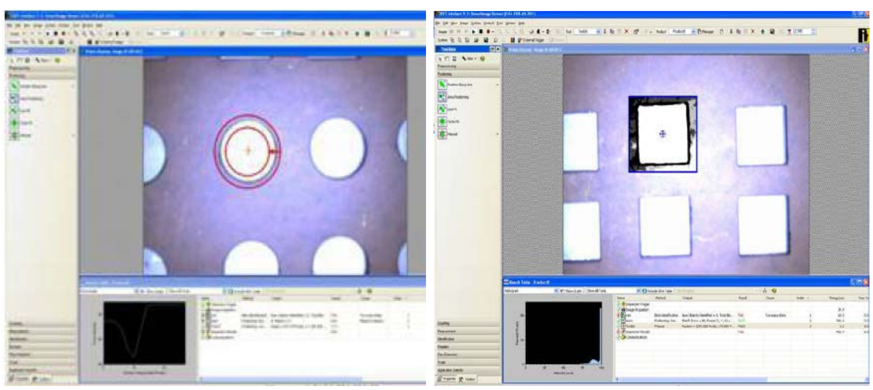


Figure 7: Image processing of circular and rectangular features to determine geometric parameters of laser-machined part features.

As with the CMM, students follow the same measurement procedures and replicate (10X) measures on a single hole to ascertain the variance of the measurement process. The data from the CMM and machine vision system correlated with each other. For a given part type and laser settings (e.g., holes and discs from set A), arrange the measurements from lowest to highest in each set: 1 set for the CMM and 1 set for the machine vision system as suggested by Figure 8. Then find the correlation coefficient and best line fit.

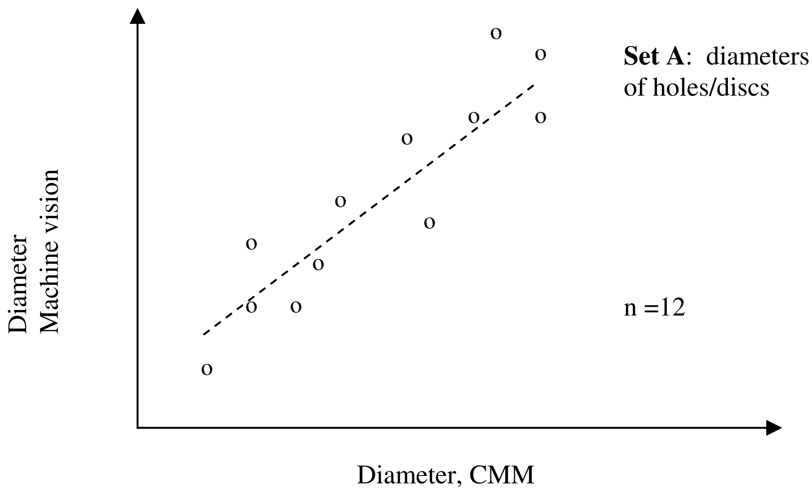


Figure 8: Hypothetical Comparison of CMM data vs. machine vision data.

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 spread sheets, including graphical presentations of resuts. Figures 9 through 12 show examples of statistical tests on laser-machined acrylic parts, with relevant details included in the figure captions. These studies show 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, and the laboratory exercises can be incorporated in courses based on other statistical software packages such as MiniTab™.

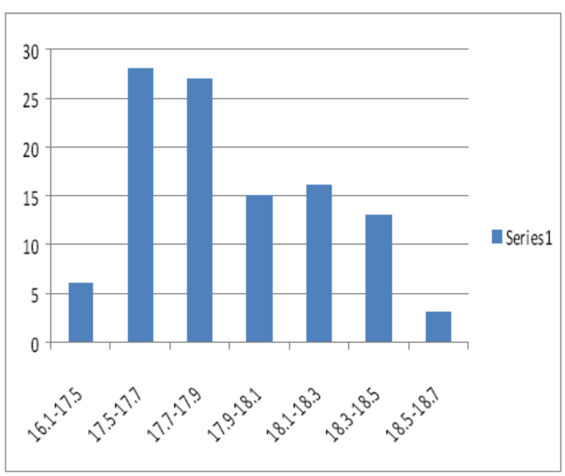


Figure 9: Binning of data for laser-machined holes according to the diameters measured by the CMM.

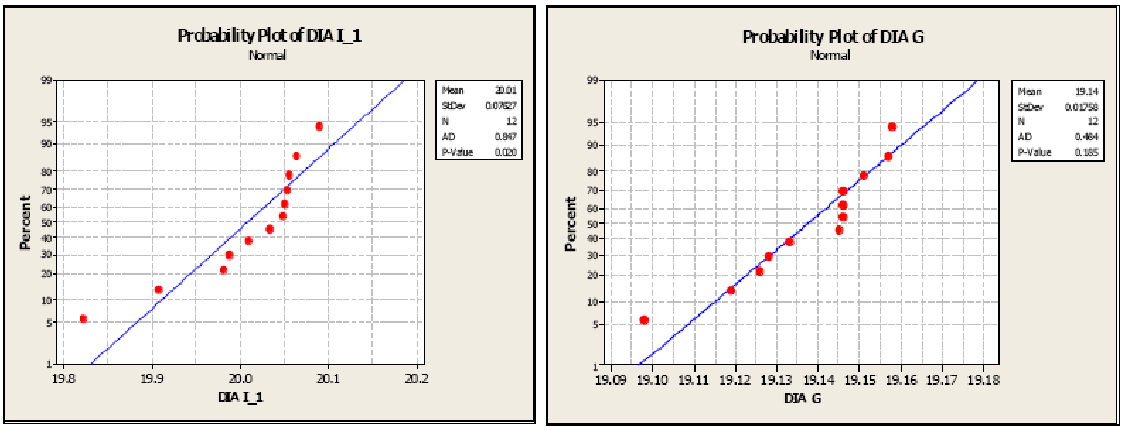


Figure 10: Probability plots for data as shown in Figure 9 and implying the data is normally distributed.

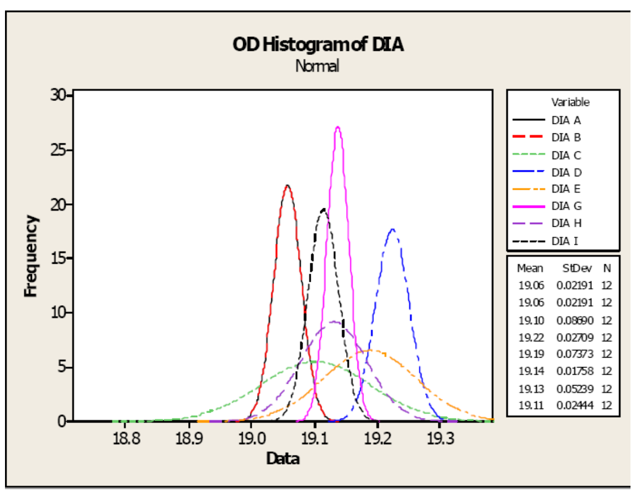


Figure 11: Distribution of data on diameters for various laser-machined circular holes.

T-Test:

CMM

t-Test: Two-Sample Assuming Unequal Variances

	A	*B*
Mean	18.256	17.9707
Variance	0.00036	0.35715
Observations	12	12
Hypothesized Mean Difference	0	
df	11	
t Stat	1.65309	
P(T<=t) one-tail	0.06327	
t Critical one-tail	1.79588	
P(T<=t) two-tail	0.12654	
t Critical two-tail	2.20099	

t-Test: Two-Sample Assuming Unequal Variances

	C	*D*
Mean	18.34842	18.44617
Variance	0.006587	0.002592
Observations	12	12
Hypothesized Mean Difference	0	
df	18	
t Stat	-3.534464	
P(T<=t) one-tail	0.001184	
t Critical one-tail	1.734064	
P(T<=t) two-tail	0.002368	
t Critical two-tail	2.100922	

t-Test: Two-Sample Assuming Unequal Variances

	E	*I*
Mean	19.18858	19.13775
Variance	0.005437	0.000309
Observations	12	12
Hypothesized Mean Difference	0	
df	12	
t Stat	2.323091	
P(T<=t) one-tail	0.019275	
t Critical one-tail	1.782288	
P(T<=t) two-tail	0.038551	
t Critical two-tail	2.178813	

Figure 12: *t*-test on hole diameters to ascertain statistical significance of differences between holes laser-machined with different laser machining parameters.

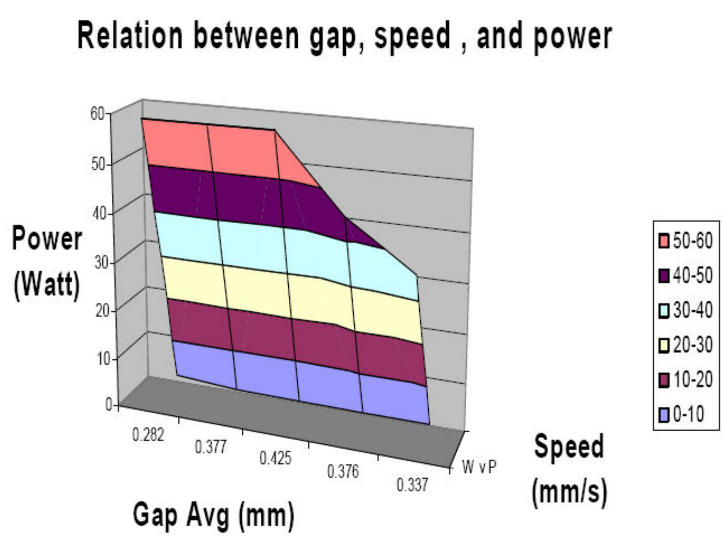


Figure 13: Surface plot showing relationship of gap to laser speed and power.

Design of Experiments (DOE)

Students used the Stat-Ease® Design of Experiments (DOE) software package from Stat-Ease, Inc. (2021 E. Hennepin Avenue, Suite 480 Minneapolis, MN 55413-2726 e-mail: info@statease.com, website: www.statease.com). 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. Figure 13 shows a 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.

Discussion and Conclusion

The study of laser-machining of acrylic plastic sheets for application to microfluidic lab-on-a-chip medical 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.

Acknowledgement

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