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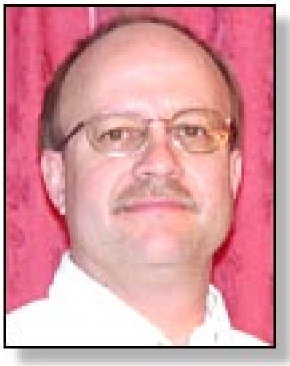

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Characterizing Productivity of a 4kw CO2 Laser Cutting System for 0.25" Mild Steel Using Central Composite Methodology

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Abstract

Laser cutting of sheet metal has become an economically viable method of production through advances in technology. Evidence of advances in laser technology has been thoroughly documented as research published in professional literature. The most relevant research available in professional literature was used to provide a basis and context for the research documented in this paper, wherein much of that research was directed toward improving the quality of cuts made by laser devices. Accordingly, researchers conducted this study to investigate increasing throughput of laser cutting operations where the quality of cuts produced by a new 4kW CO_2 laser exhibited an acceptable surface roughness. For purposes of this study, "acceptable" surface roughness was a contractually negotiated parameter of ≤ 18μm. Surface roughness of ≤ 18μm was a parameter of primary importance to and industry benchmark for metal fabricators.

This study was conducted in an operational manufacturing environment and was based on the design and analysis of a 2^4 full factorial characterization experiment later projected to a 3^4 central composite design with response surface methodology for further characterization. Input (independent) variables of the study included feed rate, power, frequency, and gas pressure while the output (dependent) variable was surface roughness. As this was an "applied" rather than empirical study, many other possible combinations of variables and settings for those variables were not considered due to expense and the discretion/interest of management at the host manufacturing facility.

Results of this study indicated that use of the most advanced laser cutting technology commercially available did not guarantee production of cut quality at ≤ 18μm in an operational manufacturing environment. Conclusions drawn from the study were that 1.) Suggested settings for process variables provided by the vendor of the laser cutting system were not valid in the host manufacturer's production environment, 2.) Cut quality was highly sensitive to changes in the input variables – particularly gas purity, and 3.) Interpretation of a response surface generated as part of the experiment design indicated an expansion of the experimental space (i.e., collection of more experimental material at levels/settings not included in the original or projected design) may be warranted.

Introduction

Industrial Technologists (ITs) are frequently called upon to engage in process improvement activities. Process improvement activities commonly involve new equipment acquisitions that are, in part, economically justified by manufacturer promises that equipment will perform at specified levels of quality. Unfortunately, there are many cases where the new equipment does not perform as promised when it is delivered for use.

When new equipment does not perform as promised, it does not necessarily mean the manufacturer has been dishonest. Much more likely is the case where promises regarding equipment performance were made in the context of rigorous research and development efforts conducted under conditions found in near-perfect laboratory conditions. Conditions found in operational manufacturing environments, however, are rarely as favorable to equipment/process operation as in the laboratory.

In practice, the person or team responsible for new equipment installation and debugging may determine it is not possible to establish process performance at a quality level specified by the manufacturer. In this case, the person or team, through use and application of rigorous analytic methods, commonly discovers discrepancies between laboratory and production environments. Typically, the person or team responsible for the equipment installation/debugging first contacts the equipment manufacturer and an attempt is made to solve problems with the support of the equipment vendor's engineering staff. Once it is determined the new equipment is working as best as it can within the given operating environment, those responsible for installation/debugging continue to work at process improvement via one of two means to include manipulation of process settings/variables "One-Factor-At-A-Time" (OFAT) or via planned experimentation with a factorial design.

In an OFAT approach to process improvement, those involved in the work effort adjust one process parameter at a time to investigate what happens to process performance. Interaction of process variables in industrial operations is a common occurrence however, and to investigate interactions with the OFAT approach requires more data collection and analysis than with a factorial design. In factorial designs, variables and settings are manipulated in combinations as will be described in this paper.

In this paper readers will become familiar with a case where the researchers were responsible for new equipment acquisition. In this case, the new equipment did not perform as initially expected in an operational manufacturing environment. Planned experimentation was then employed to scientifically investigate the conditions under which the equipment performance could be improved. The new equipment was an industrial-grade laser cutting system used for cutting operations on sheet metal products. Concerns for quality of output from the laser cutting system in this application were consistent with use of this type of equipment in the larger industrial community as it is imperative the company employing the laser cutting system remain competitive within the national market for sheet stock cutting and fabrication services.

Background

A primary concern for users of production laser systems continues to be maximizing throughput (i.e., feed rate) while maintaining acceptable quality of the cut edge measured as surface roughness ≤ 18μm. Poor quality can be described by a variety of undesirable characteristics such as: excessive roughness, kerf width variations resulting in part tolerance errors, kerf material sticking to work surfaces (excess dross), gross deformation of cut surfaces (blowouts), and metallurgical changes in the heat affected zone (HAZ).

Laser cutting operations generally produce regular patterns in the cut surface, known as striations. The severity (frequency and amplitude) of these striations has a direct impact on surface quality. The mechanism of creating these striations has been the topic of many other researchers' work - Di Pietro, P., Yao, Y.L. (1994, 1995), Biermann, S., Nuss, R., Geiger, M. (1998), et al. Additional roughness can be observed when there is excessive side-burning in thicker materials (>.08"). Conditions resulting in side burning in materials thinner than .08" usually result in blowouts. Incomplete cuts can result from low oxygen pressure, focus lens deterioration, and/or trying to cut at a rate exceeding the power rate required for maintaining complete cutting.

Purpose

The purpose of this research was to: 1) Characterize the performance of a newly installed 4kW laser system to provide baseline data for quality and productivity analysis, and 2) Determine the settings of controllable factors for maximizing acceptable quality. The scale of measurement for "acceptable quality" was surface roughness (R_{ms} where R_{ms} = the average surface roughness at the manufacturer's recommended process settings) measured in micrometers (μm) where the required value of roughness was ≤ 18μm which was the industry standard. Accordingly, the researchers investigated the hypotheses that related selected operating conditions/settings to output quality measured as surface roughness.

Hypotheses

1. $H_o: R_{ms\ a} = 18\mu m$

   $H_o: R_{ms\ a} \neq 18\mu m$

Where surface roughness ≤ 18μm is the industry standard for quality

Methodology

Laser system description

This study was conducted on a newly installed Mazak model STX-Mk II, (4kW CW CO_2). Recommended settings for cutting 0.236" mild steel are given below. These settings, according to Mazak, were based on assist gas purity of 99.95% and ideal material conditions (free of surface impurities and having a homogenous consistency throughout).

When the system was being evaluated for possible purchase, the equipment vendor provided samples of 0.25" steel displaying an almost polished edge appearance with minimal striation. The process settings under which the demonstration samples were manufactured were, unfortunately, not provided. The manufacturer did not provide any empirical evidence of expected cut quality at their recommended settings. Discussions with the manufacturer indicated their method of surface quality measurement was only by judgment of visual quality.

The manufacturer's recommended settings produced unacceptably rough cuts with blowouts and, excess dross.
The recommended cut conditions were as follows:

Feed rate: 100 in/min
Power: 3000W
Frequency: 1000hz
Gas pressure: 0.5 Mpa

Since this experiment was conducted to characterize a new laser cutting system using the manufacturer's recommended settings for cutting 0.25" thick mild steel sheet in an oxygen-rich environment, the output characteristic of cut quality was measured to provide baseline data for comparison with future results. For purposes of this experiment, assist gas purity, ambient temperature, humidity, and material conditions were variables in the operational manufacturing environment that were not possible to control. Variables that were controlled included feed rate, power, laser pulse frequency, and assist gas pressure. Settings for the controlled variables in this study were as follow:

Feed rate: 80 in/min - 100 in/min
Power: 2000W – 3000W
Frequency: 300hz – 550hz
Gas pressure: 0.5 Mpa – 0.8 Mpa

Description of factors that were controlled:
Feed rate – Two settings for *feed rate* were investigated in this study (80 and 100 in/min respectively). Higher feed rates are desirable as process throughput is directly related to profitability.

Power – The manufacturer recommended settings of 3000 Watts for cutting 0.25" steel. This in combination with other vendor recommended settings produced excessive roughness of the cut surface. Experienced laser operators at the host facility recommended lower power settings combined with other changes to recommended cut conditions. Settings of 2000 and 3000W were selected for experimentation.

Laser pulse *frequency* - Otherwise known as "pulsing", *frequency* is commonly known to have the effect of reducing the Ra value of cut surface roughness by interrupting the natural frequency of striation formations. Settings of ≥ 800hz are considered to be continuous wave. Powell, J., King, T.G., Menzies, I.A. (1985) studied the interactions of feed rate and pulse *frequency*, finding that laser pulse frequencies on the order of twice the natural striation frequency produced significant improvements by having a canceling effect on striations. The frequency of striations is not necessarily correlated with cutting speed, it is cyclical in regard to the ignition, burning, extinguish, and oxidation phenomenon described by Ivarson, A., Powell, J., Kamalu, J., Magnusson, C. (1994) who found that at a cutting speed of ~70in/min, at a *frequency* of 400-500hz, cutting quality was dramatically improved. While their research was conducted on 1.25mm steel (18ga) at relatively low power (350W), their research suggested that *frequency* could be an important factor in achieving reasonable quality at high feed rates in thicker materials.

Assist *gas pressure* – According to O'Neill, Gabzdyl (2000), the risk of side-burning increases with material section thickness due to work piece overheating as the oxygen gas jet reacts with the surrounding material in the kerf area outside the cutting zone. At low cutting speeds, the energy from the process conducts away from the interaction point and elevates the local temperature of the metal further away from the cutting point. If the local temperature approaches 1000°C the kerf width tends to increase, resulting in deep gouging and uncontrolled side-burning. In the relevant literature, it was interesting to note that thicker materials may be cut better using lower oxygen pressure than were thinner materials. For 0.236 – 0.25" hot-rolled, pickled, and oiled steel (HRPO), the system manufacturer recommends 5 kg/cm² (= 0.5 MPa / = 71 lb/in²). Settings of 0.5 MPa (5 kg/cm²) and 0.8 MPa (8 kg/cm²) were chosen for experimentation because higher cutting speeds with high quality are desrired.

Description of factors that were not controlled:
Focus lens condition - Focus lenses deteriorate over time as the beam energy induces thermal effects and back splatter from the material being cut collects on it. The lenses are cleaned periodically to extend their service life, but eventually must be replaced.

Nozzle gap - The gap between the work surface and the tip of the gas jet nozzle remains, to an extent, a function of the nozzle design. The nozzle gap is set to a point that provides a back pressure to control the gas flow into the kerf as the material is being cut. Such gaps are generally not dependent upon material type or thickness. Setting the gap too close will damage the tip from back splatter and debris collecting on the material surface. Setting the gap too far away will reduce the effectiveness of the gas flow into the kerf.

Assist gas purity - The assist gas is purchased in bulk liquid form, and is certified by the supplier to a purity level (between 99.6% and 99.997%). Assist gas purity can be improved, but only by purchasing laboratory grades in small quantities. Since laboratory grade gasses dramatically increase operating costs, they remain a non-viable option for process improvement. Therefore, assist gas purity was not considered a controllable factor. Discussions with the sales agent for the host facility's supplier for oxygen assist gas indicated that the purity level was about 99.7%. This was an average value over time as shipments were added to the remainder of the tank when it was refilled. Since the production-grade assist gas purity available (99.7%) was lower than that specified by the equipment vendor (99.95%) it was anticipated quality would likely be degraded as a function of this factor alone. A study by Powell, Ivarson, Kamalu, Borden, Magnusson, [13] (1992) documented that cutting speed was very sensitive to contamination in the oxygen supply. At 99.6%, the cutting speed may be reduced to approximately 80% of theoretical maximum as compared to a purity level of 99.998%.

Assist gas
The assist gas used was oxygen. Other gases are used for different materials.

Materials
The experiments was conducted using 0.25" HRPO (hot-rolled, pickled and oiled) laser quality steel plate, a low carbon mild steel used extensively for a wide variety of general fabrication applications.

Experimental Limitations and Delimitations
The laser system manufacturer (Mazak) made no claim the values given in the cutting parameter tables provided with the system were optimized in recognition of the fact variability is inherent from system to system. Determination of the high and low settings for each variable was based on recommendations from experienced laser operators and programmers who had good intuition regarding the practical limits to be considered.

Environmental conditions of ambient temperature and humidity were considered to be uncontrollable as they ranged between 50 – 80°F, 30-80% relative humidity respectively.

This study was restricted to cutting in a straight line. Tightly curved geometry such as small holes and radii, and small features such as notches and fine detail created by short lines were not considered. There was a minimum of 0.5" spacing between run groupings to prevent metallurgical changes in a fresh cut that resulted from an adjacent cut. The width of the heat affected zone (HAZ) next to the cut edge was <0.12".

There was no consideration of cut location within a sheet. The profile gauge was considered to be "capable" and the calibration was considered to be adequate for the measurement task. ASTM D4417 Method B was the measurement standard used for all measurements.

Sampling methods
The system was programmed to cut three 2"x2" squares for each sample run, providing twelve locations from which roughness was measured for each run. Ten measurements are required for minimum compliance with ASTM D4417 Method B for averaging individual measurements. All runs were observed by the researchers to verify run order, machine settings, and correlation of the samples to the intended run. Documentation for test conditions and settings were prepared and affixed to each sample as the experimental runs were conducted. Material handling and storage of the samples ensured the integrity of test results.

Cut quality was measured with a mechanical surface profile gauge (Elcometer model #123) that was calibrated by a calibration technician using a National Institute of Standards and Technology-traceable "working standard."

Initial experimental design
A 2^4 full-factorial fixed effect experiment was conducted with three (3) replicate. Surface quality (target Ra 18μm at maximum feed rate) was the response variable. Two levels of feed rate were used to study the effects of the other factors. Run order was randomized by use of JMPIN 5.1 statistical analysis software.

Experiment design projection
In the initial experiment it was determined that frequency had no significant effect on roughness. Since it was determined that frequency was not a statistically significant variable, the design was projected to a 2^4 full factorial to improve accuracy of the results. For the remainder of this paper results of the study will be focused on analysis and interpretation of the 3^4 central composite design which was the final experiment design after projection.

Analysis
All analysis was conducted at $\alpha = .05\%$ confidence.

Discovery of a non-significant factor (frequency) provided justification for use of a statistical technique known as projection. When using design projection as described by Montgomery (2001), data from an initial experiment design are used as data input to a new design. In this case, data from the original 2^4 were transferred to a new 3^4 central composite design using star point settings to facilitate creating response surface geometry. New runs (i.e., new experimental material) were identified and tracked by the use of a blocking factor.

Table 1 (below) provides the run order, orthogonal pattern, machine settings for

Table 1, ***Parameter Estimates***

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	23.152083	21.66044	1.07	0.2895
Feed rate(80,100)&RS	8.3722222	1.201274	6.97	<.0001
Power(2000,3000)&RS	8.1962963	1.201274	6.82	<.0001
Frequency(300,550)&RS	0.3759259	1.201274	0.31	0.7554
Gas Pressure(0.5,0.8)&RS	-2.109259	1.201274	-1.76	0.0843
Feed rate*Power	2.1604167	1.274144	1.70	0.0952
Feed rate*Frequency	0.56875	1.274144	0.45	0.6570
Power*Frequency	0.4604167	1.274144	0.36	0.7191
Feed rate*Gas Pressure	-4.439583	1.274144	-3.48	0.0009
Power*Gas Pressure	4.96875	1.274144	3.90	0.0002
Frequency*Gas Pressure	-0.964583	1.274144	-0.76	0.4520
Feed rate*Feed rate	-5.133333	6.242003	-0.82	0.4142
Power*Power	1.4166667	6.242003	0.23	0.8212
Frequency*Frequency	1.4	6.242003	0.22	0.8233
Gas Pressure*Gas Pressure	1.9	6.242003	0.30	0.7619
Block[2-1]	2.5145833	16.95138	0.15	0.8826

the controlled factors, roughness response values, blocking factors, residuals, and transformed data values.

1. Estimate factor effects

The strength of the main effects provided in *Table 1* (previous page) indicated *feed rate (p<0.0001)* and *power (p<0.0001)* were statistically significant at $\alpha = .05$. *Gas pressure (p=0.084)* was also determined to be statistically significant at $\alpha = .05$. *Frequency (p=0.755)* was found to have no significant impact on these results at =.05. The strength of interaction effects indicated that significant interaction terms were *feed rate * gas pressure (p=0.0009)*, and *power * gas pressure (p=0.0002)*. All other interaction terms were found not to be significant since p-values for them were *p>0.05*. Additional interaction terms found in *Table 1* (previous page) (*feed rate * feed rate, power * power, frequency * frequency, and gas pressure * gas pressure*) were quadratic terms used to show curvature in contour plots.

The *block* term p-value of 0.883 was not statistically significant at $\alpha = .05$ due to error between the original runs and the center point runs.

2. Form initial model

Design projection

Because *frequency* and *block* were found not to be significant either as a main effect, or in any interaction terms, the design was projected to a 3^3 central composite design by removing these non-significant terms. Removing the terms projected the design that effectively replicated the original 48 runs a total of 6 times, and the 27 center point runs a total of 3 times.

Regression model

Using the parameter estimates from *Table 1,* the regression model for the 3^3 central composite model became:

$$+\frac{1}{2}(8.372)_{x1}+\frac{1}{2}(8.196)_{x2}+\frac{1}{2}(-2.109)_{x4}+\frac{1}{2}(2.160)_{x1,x2}$$

$$+\frac{1}{2}(-4.440)_{x1,x4}+\frac{1}{2}(4.969)_{x2,x4}+\frac{1}{2}(-6.067)_{x1,x1}+\frac{1}{2}(0.483)_{x2,x2}+\frac{1}{2}(0.967)_{x4,x4}$$

Figure 1. Contour Profiler Feed rate * Power

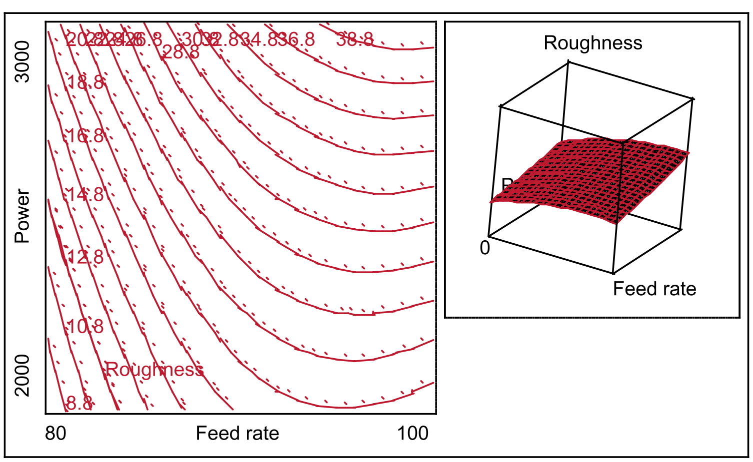


Table 2. ***Analysis of Variance***

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	10346.823	1034.68	14.1510
Error	64	4679.500	73.12	Prob > F
C. Total	74	15026.323		<.0001

y= 27.352

where: x1 = feed rate
x2 = power
x4 = gas pressure

3. Perform statistical testing

See table 2 below.

The model indicated the presence of at least one significant term (F=14.151, p<0.0001).

Contour profiles

The following tables and graphs were provided as illustrations of the effects of each of the two-factor interactions. By using the simulation (profiler) features in JMPIN 5.1, each interaction was adjusted for maximum desirability (minimum values for roughness at maximum feed rate). Using the predicted variance (±5.794 µm) from the projected 2^3 design, the contour line nearest 12µm was observed as the nominal value to help assure a maximum value of 18µm. The desirable region was determined using the method of steepest descent [Montgomery, D.C. (2001)].

The combination of factor settings in the interaction effect of *feed rate * power* suggested that acceptable values of roughness may be achieved at a *feed rate* of 83.148 in/min with the *power* set to 2000W. The setting for *gas pressure* was set by JMPIN 5.1 to its center point value of 0.65 Mpa.

In the contour plot (*Figure 1*), it was observed that the region of desirability was to the lower left of the contour line representing 12µm where the minimum settings for *power* (2000W) and minimum setting of *feed rate* (80 in/min) were displayed. This region indicated that slightly faster feed rates may be possible without sacrificing roughness to beyond 12µm ±5.794µm.

The combination of factor settings in the interaction effect of *feed rate * gas pressure* in *Figure 2* (next page) suggested that acceptable values of roughness may be achieved at a *feed rate* of 86.667 in/min with the *gas pressure* set to 0.8 Mpa.

In the contour plot, it was observed that the region of desirability was to the left of the contour line representing 12µm where the maximum settings for *gas pressure* (0.8 Mpa) and minimum setting of *feed rate* (80 in/min) were displayed. The region widened as values for *gas pressure* increased. This region indicates that slightly faster feed rates may be possible without sacrificing roughness to beyond 12µm ±5.794µm. There is an appearance of a region in the upper right corner where the contour lines change direction to descending slopes. This may be the region where a group of three samples occurred from the same settings in all replicates which were found to be acceptable at 90-100 in/min.

The combination of factor settings in the interaction effect of *power * gas pressure* suggested that acceptable values of roughness may be achieved at a *feed rate* of 86.667 in/min with the *gas pressure* set to 0.8 Mpa The setting for *power* and *gas pressure* was set by JMPIN 5.1 to values of 2000W and 0.8 Mpa respectively, which were carried over from the previous profiler setting.

Figure 2. Contour Profiler Feed rate * Gas pressure

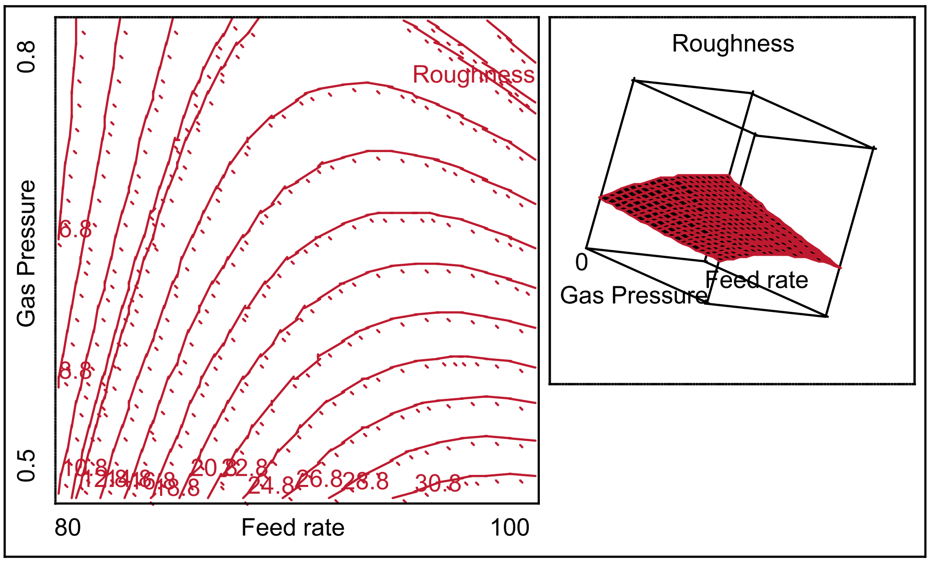
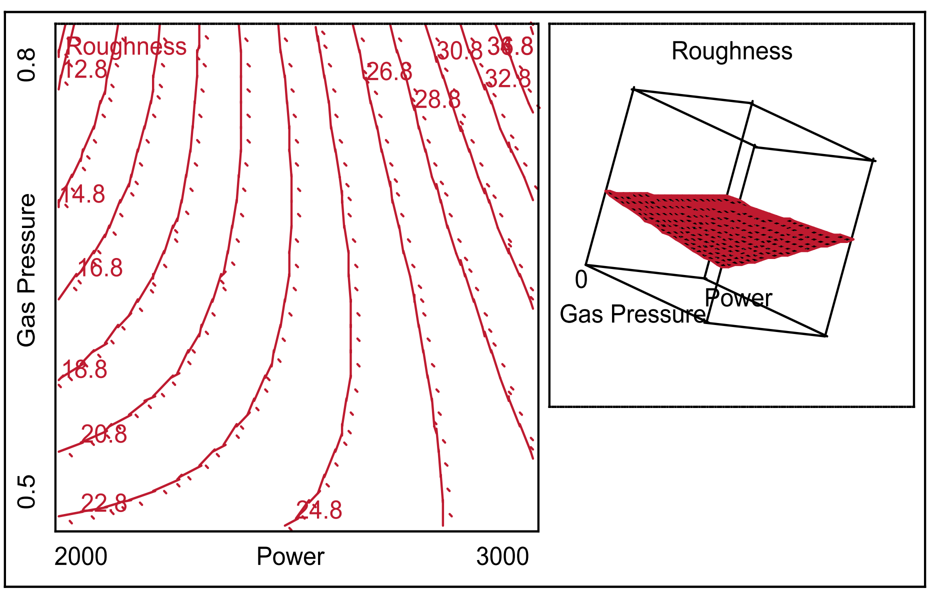


Figure 3. Contour Profiler Power * Gas pressure



In the contour plot in *Figure 3*, it was observed that the region of desirability was in the extreme upper left corner where the maximum settings for *gas pressure* (0.8 kg/cm²) and minimum setting of *power* (2000W) were displayed. There was little or no room to increase *power* or reduce *gas pressure* without sacrificing roughness to beyond 12µm ±5.794µm. The analysis of this study indicated that acceptable results may be obtained using:

Feed rate: 80 in/min
Power: 2000W
Gas pressure: 0.8 Mpa
Frequency: 300 or 550 hz

Summary and conclusions

General observations

A surprising amount of variation between observations of experimental runs was observed. In this case, either the cut surface was very well within the acceptable limits established (Ra ≤ 18µm), or they were very poor. The greater the roughness values became, the wider the variations among the individual measurements became.

For the samples that exceeded the acceptable roughness value, most had varying degrees of side burning, excess dross, and major deviations in kerf width from the top surface to the bottom. There was also excessive variability in test cut surface quality.

The contour plots indicated there were extensions of the desirable regions outside the range of factors settings selected for this study. In the *power * feed rate* contour plot (*Figure 1*), a possible region was observed in the area below a *power* setting of 2000W.

In the contour plot for *feed rate * gas pressure (Figure 2)*, there was an appearance of a region in the upper right corner where the contour lines change direction to descending slopes. This is the region where a group of samples were found to be acceptable at 90-100 in/min, but could not be supported by the analysis.

In the contour plot for *power * gas pressure (Figure 3),* it appeared that the desirable region extends into settings for *gas pressure* that are higher than the maximum setting (0.8 Mpa) used in this study.

Conclusions

Conclusions drawn from the study were that 1.) "Suggested" settings for process variables provided by the vendor of the laser cutting system were not valid in the host manufacturer's production environment, 2.) Cut quality was highly sensitive to changes in the input variables – particularly gas purity, and 3.) Interpretation of a response surface generated as part of the experiment design indicated an expansion of the experimental space (i.e., collection of more experimental material at levels/settings not included in the original or projected design) may be warranted.

Implications for future study

The contour plots suggest exploration of regions outside the design space selected for this study where the ranges for the factors included in the final 3^3 design might be:

Feed rate: 80 in/min – 100 in/min
Power: 1500W - 2000W
Gas pressure: 0.8 kg/sq-cm – 1.2 kg/sq-cm
Frequency: 100hz – 500hz or 500hz – 750hz (to again study the effects of this factor under different conditions)

References

Biermann, S., Nuss, R., Geiger, M. (1998) *Analytical studies on laser cut surfaces*, SPIE, 7th International Symposium on Gas Flow and Chemical Lasers 1031 586-591.

Di Pietro, P., Yao, Y.L. (1994) *An investigation into characterizing and optimizing laser cutting quality-a review*, International journal of machine tools & manufacture, Vol 34, #2, pp.225-243,

Di Pietro, P., Yao, Y.L. (1995) *A new technique to characterize and predict laser cut striations,* International journal of machine tools & manufacture,Vol. 35, No. 7 pp. 993-1002

Ivarson, A., Powell, J., Kamalu, J., Magnusson, C. (1994) *The oxidation dynamics of laser cutting of mild steel and the generation of striations on the cut edge*, Journal of Materials Processing Technology 40 359-374.

Montgomery, D.C. (2001) *Design and Analysis of Experiments – 5th Edition* – Wiley

Nagarajan, R. (2000) *Parametric study of the effect of laser cutting variables on the cut quality*, Master Thesis, Wichita State University, Wichita, Kansas.

O'Neill, W., Gabzdyl, J.T. (2000) *New developments in laser assisted oxygen cutting,* Optics and lasers in engineering, Vol. 34, pp. 355-367

Powell, J., Ivarson, A., Kamalu, J., Borden, G., Magnusson, C. (25-29 October 1992) *The role of oxygen purity in laser cutting of mild steel,* ICALEO '92, laser materials processing :, Orlando, Florida

Powell, J., King, T.G., Menzies, I.A. (26-28 March 1985) *Cut edge quality improvement by laser pulsing,* Proceedings of the 2nd International Conference on Lasers in Manufacturing, Birmingham, U.K., pp. 37-45

Steen, W.M., Kamalu, J. N. (1983) Laser Cutting, Laser Materials Processing, M. Bass (ed.) *North Holland Publishing Company*, New York, Vol. 3, pp. 17-111.