KCP--613-5737

Laser Scribe Optimization Study

Federal Manufacturing & Technologies

A. L. Wannamaker

KCP-613-5737

Published September 1996

Final Report

Approved for public release; distribution is unlimited.

RECEIVED

OCT 02 1996

OSTI

MASTER

Prepared Under Contract Number DE-ACO4-76-DP00613 for the
United States Department of Energy

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

AlliedSignal
AEROSPACE

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade names, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

Printed in the United States of America.

This report has been reproduced from the best available copy.

Available to DOE and DOE contractors from the Office of Scientific and Technical Information, P. O. Box 62, Oak Ridge, Tennessee 37831; prices available from (615) 576-8401, FTS 626-8401.

Available to the public from the National Technical Information Service, U. S. Department of Commerce, 5285 Port Royal Rd., Springfield, Virginia 22161.

A prime contractor with the United States
Department of Energy under Contract Number
DE-ACO4-76-DP00613.

**AlliedSignal Inc.
Federal Manufacturing & Technologies
P. O. Box 419159
Kansas City, Missouri
64141-6159**

Approved for public release; distribution is unlimited.

LASER SCRIBE OPTIMIZATION STUDY

A. L. Wannamaker

Published September 1996

Final Report

A. L. Wannamaker, Project Leader

Project Team:

Joyce Anderson

Lee Anderson

Larry Atkinson

Carl Boehning

John Grice

Bill Lepley

Jack McGrath

Steve Penyock

Bill Rowe

Bob VanCleave

Ray Wolfe

DISCLAIMER

**Portions of this document may be illegible
in electronic image products. Images are
produced from the best available original
document.**

CONTENTS

<i>Section</i>	<i>Page</i>
Abstract	1
Summary	1
Discussion	2
Scope and Purpose	2
Prior Work	2
Activity	2
Project Approach and Methodology	2
Implementation of Experiment	10
Statistical Analysis	13
Recommendations, Controls, and Conclusions	15
Accomplishments	15
Appendix. Experimental Design and Data	16

ILLUSTRATIONS

<i>Figure</i>		<i>Page</i>
1	Pressure Vessel Laser Scribe Operation.....	3
2	Failure Mode and Effect Analysis Results.....	6
3	Measurement System Evaluation Results	8
4	Accuracy Validation.....	11
A-1	Initial Experimental Design Matrix	25
A-2	Laser Scribed Test Coupons.....	30
A-3	Summary Matrix: Measurement Results of Response Variables.....	35
A-4	SEM Photographs of Cracks and Spatters	52
A-5	Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot	60
A-6	Recommended Variable Settings for Experimental Substrates.....	66

TABLE

<i>Number</i>		<i>Page</i>
1	Process Distributions for Penetration Variable	15

ABSTRACT

The laser scribe characterization/optimization project was initiated to better understand what factors influence response variables of the laser marking process. The laser marking system is utilized to indelibly identify weapon system components. Many components have limited field life, and traceability to production origin is critical. In many cases, the reliability of the weapon system and the safety of the users can be attributed to individual and subassembly component fabrication processes. Laser beam penetration of the substrate material may affect product function. The design agency for the DOE had requested that FM&T characterize the laser marking process and implement controls on critical process parameters.

SUMMARY

The six sigma methodology was applied to the laser scribe characterization/optimization project. Team members first generated a detailed process map which identified critical process parameters. Failure mode and effects analysis was also conducted to ensure that characterization efforts were in line with customer priorities. A level two, four factor, full factorial design of experiment was conducted to establish the main effects on laser scribe penetration, marking legibility, and the existence of micro cracks and splatters. The analytical laboratory at AlliedSignal Inc., Federal Manufacturing & Technologies (FM&T), was chartered with data collection on the response variables. An IBAS image analyzer and scanning electron microscope were used to quantify experimental results. Numerous statistical tools were used to conduct analysis of measured results, and predicted individual results could be determined with a 95% confidence.

DISCUSSION

SCOPE AND PURPOSE

Three objectives were established for this study:

1. To determine if vapors produced by laser marking represent a health hazard,
2. To optimize laser scribe parameters for specific substrates, and
3. To analyze the tendencies of the laser marking process to generate micro cracks and spatters.

The laser marking system is used to indelibly identify weapon system components. Many components have limited field life, and traceability to production origin is critical. Also, in many cases, the reliability of the weapons system and the safety of the final users can be attributed to individual and subassembly component fabrication processes.

PRIOR WORK

A literature search on laser scribe characterization and process safety issues was unsuccessful. Customer need for ensured laser scribe process controls could only be achieved by independent research by FM&T personnel.

ACTIVITY

Project Approach and Methodology

The six sigma methodology was chosen to accomplish characterization and control of the laser scribe operation. Process mapping/characterization of a typical laser marking process was conducted, and the "vital few" independent process variables were identified (see Figure 1). The remaining process variables were held constant.

Process Mapping was conducted by team members. A typical laser scribe operation was analyzed by the group. The process was broken down into various stages, ranging from powering up the system to packing the completed components. Process parameters (independent process variables) were categorized as controllable (C), standard operating procedures (SOP), or noise (N).

Standard Operating Procedures (SOP) encompass process variables that are covered under documentation requiring that certain factors be monitored and maintained to ensure control.

Figure 1. Pressure Vessel Laser Scribe Operation

Controllable (C) entails process parameters that can be manipulated to see their effect on the product parameters (response variables). These **controllable parameters** will be understood fully and can be further broken down into the following groups:

1. Have no effect on the product parameters;
2. Have significant effect on distribution of product parameters but need only operate in a specific window or range;
3. Have a significant effect and must be driven to a certain target.

Noise (N) factors are too costly to control or are preferably not controlled.

Laser Marking Process -- Independent Variable Listing	
* Beam current/power	Part coating
* Substrate type	* Pulse frequency rf
Continuous pulse	* Part positioning
* Focal length setting	Character spacing
Marking radius	Filament replacement/degrade
Beam density	Part heat treat/hardness
Part curvature	Calibration variation
Offset from (x,y) (0,0)	* Beam feed rate
Beam width	Relative power
Repeat passes	Character height
Calibration variation	Beam travel (x,y)
* Deviation from optimum	Surface finish/reflectance
focal length	
Character height	
* Denotes independent variables included in design of experiment.	

Cognizant team members established the process variable categorization depicted in Figure 1 by consensus. Those "controllable" parameters shown as ***bold italicized*** will be manipulated in the initial experiment to determine their impact on product parameters.

Failure Mode and Effect Analysis (FMEA) was conducted by team members to ensure that process optimization efforts are in line with customer requirements. Potential product failures, as related to the laser scribe operation, were investigated. The effect of each failure mode on the customer was ranked by severity. Loss of part traceability and loss of component function were identified as the most deleterious failure modes the customer could experience. Causes for these types of failures were identified, and specific actions designed to eliminate the causes were developed (see Figure 2).

Columns listed in the FMEA are described below and illustrated in Figure 2:

Part/Process	Overall process under review.
Failure Mode	Types of failures that would be detrimental to the customer.
Failure Effects	The result of experiencing the above-mentioned failure mode.
SEV	The severity ranking of a specific failure (1 low to 5 high).
Causes	Possible causes for a failure.
Occurrence	Probability of a failure occurring (1 low - 5 high).
Controls	Existing or possible controls for preventing the cause of a failure.
DET	Producer ability to detect failures before reaching the customer.
RPN	Risk Priority Number = the product of Sev x Occ x Det. Identifies what area to concentrate team energies.
Action	Actions directed toward reducing individual RPNs.

It was determined that a design of experiment would be needed to characterize and optimize the laser scribe process and eliminate product variability that could result in product failures with sever customer impact.

A design of experiment was developed where attribute and variable data were utilized to determine which process parameters generated the desired response variables. Marking legibility with minimal impact on parent material (micro cracks, splatters, and penetration) and the resultant effect on product function have been established as acceptance criteria.

Visual ranking with both the aided and unaided eye was performed. Penetration of the laser scribe was quantified using an IBAS image analyzer.

Measurement System Evaluation (MSE) was conducted by team members to validate the capabilities of the equipment (see Figure 3). The chart in Figure 3 can be interpreted to confirm that the IBAS image analyzer demonstrates acceptable repeatability and resolution for performing laser scribe penetration measurements.

The control chart (Figure 3) depicts average part measurements made by different operators. The same six parts were measured two times each by each operator. The average of the two readings is recorded on the control chart.

Part/process	Failure Mode	Failure Effects	S E V	Causes	O C C	Controls	D E T	R P N	Actions	Plans	p S	p O	p D	p r p n
Pressure Vessel laser scribe	illegible/non-indelible	loss of part identity	5	scribe too light	5	qualify scribing program	1	25	laser scribe opt. exp.	comp.	5	1	1	5
			5	contamination on part surface	1	verify part cleanliness	1	5	cleaning and handling cert.	comp.	4	1	1	4
			5	laser scribe equip malfunction	2	periodic maintenance sch	1	10	Schedule developed needs validation		5	1	1	5
			5	setup incorrect	5	certify op. on laser equip. use	1	25	part specific cert. in-process		5	1	1	5
			5	wrong scribing program used	3	part specific programs	3	45	part specific cert. in-process	comp.	5	1	1	5
			5	wrong marking	4	verify at laser operation	1	20	develop ROBUST system for verif.		5	1	1	5
			5	incorrect input	2	operator vary	2	20	develop verification plan		5	1	1	5
			5	part fixture stability	2	rigid, dead stop fixtures	2	20	define fixturing		5	1	1	5
			5	incorrect equip. utilization	3	certify operator/SOP	1	15	Equipment certification		5	1	1	5
			5	machine malfunction	2	PM and first piece	2	20	Schedule developed needs validation		5	1	1	5
	excessive laser penetration	loss of part function	5	excessive beam penetration	5	system program parameters	4	100	characterize and control process	comp.	5	1	3	15
			5	program var. interaction	5	Operator certification	2	50	Part specific programs being devl.	comp.	5	1	1	5
			5	beam current too high	5	certified programs	2	50	Part specific programs being devl.	comp.	5	1	1	5
			5	pulse rate incorrect	3	certified programs	2	30	Part specific programs being devl.	comp.	5	1	1	5
			5	feed too slow	5	certified programs	2	50	Part specific programs being devl.		5	1	1	5
			5	Calibration	4	SOP	1	20	DOE to validate cal impact on perform.		5	1	1	5
			5	Beam alignment	2	SOP	2	20	Calibration validation	A/R	4	1	1	4
			5	lens distortion	1	SOP	1	5	Low priority at this time		5	1	1	5
			5	power fluctuations	1	noise	2	10	Low priority at this time		5	1	1	5

Figure 2. Failure Mode and Effect Analysis Results

Part/process	Failure Mode	Failure Effects	S E V	Causes	O C C	Controls	D E T	R P N	Actions	Plans	p S	p O	p D	p r p n
	generation of micro cracks	compromise part integrity	4	setup incorrect	3	certify op. on laser equip. use	2	24	part specific cert. in-process		4	1	1	4
			4	wrong scribing program used	3	part specific programs	2	24	part specific cert. in-process		4	1	1	4
			4	incorrect equip. utilization	3	certify operator/SOP	2	24	Equipment use certification		4	1	1	4
			4	machine malfunction	2	PM and first piece inspect	2	16	Schedule developed needs validation		4	1	1	4
Pressure Vessel laser scribe	generation of micro cracks(cont)	compromise part integrity	4	program development	3	Operator certification	1	12	Part specific programs being devl.		4	1	1	4
	generation of spatters	compromise part integrity	4	program not optimized	4	Results not analyzed by engr.	2	32	DOE to be conducted		4	1	1	
			3	setup incorrect	3	certify op. on laser equip. use	2	18	part specific cert. in-process		3	1	1	3
			3	wrong scribing program used	3	part specific programs	2	18	part specific cert. in-process		3	1	1	3
			3	incorrect equip. utilization	3	certify operator/SOP	2	18	Equipment use certification		3	1	1	3
			3	machine malfunction	2	PM and first piece inspect	2	12	Schedule developed needs validation		3	1	1	3

Figure 2 Continued. Failure Mode and Effect Analysis Results

MEASUREMENT SYSTEM EVALUATION: IBAS IMAGE ANALYZER

MEASUREMENT SYSTEM EVALUATION: IBAS IMAGE ANALYZER															Part No. 1470110.		Chart No.		
Part/Assy Name Laser Scribe Pressure Vessel								Parameter Laser Penetration				Operation			Specification Limits .0003/.0012"				
Operator Analytical Lab.				Machine IBAS Image Analyzer					Gage Stage Mic.			Unit of Measure Micro in.			Zero Equals				
Date		9/11/95								9/11/95									
Time		8:00								8:00									
Operator		Dave							Bill										
Part		1		2		3		4		5		6							
Sample Measurements	1	577		467		604		692		682		627				627			
	2	600		513		545		673		660		627				614			
	3																		
	4																		
	5																		
Sum		1177		980		1149		1365		1342		1254				1241			
Average $\bar{X}$		588.5		490		574.5		682.5		671		627				620.5			
Range, R		23		46		59		19		22		0				13

Figure 3. Measurement System Evaluation Results

UCL Xbar	675.335	675.335	675.335	675.335	675.335	675.335	675.335	675	675.335	675.335	675.335	675.335	675.335	675.335	675.335	675.335
X Dbl. Bar	623.79	623.79	623.79	623.79	623.79	623.79	623.79	####	623.79	623.79	623.79	623.79	623.79	623.79	623.79	623.79
LCL Xbar	572.2483	572.2483	572.2483	572.2483	572.2483	572.2483	572.2483	572	572.2483	572.2483	572.2483	572.2483	572.2483	572.2483	572.2483	572.2483
UCL Range	89.6525	89.6525	89.6525	89.6525	89.6525	89.6525	89.6525	####	89.6525	89.6525	89.6525	89.6525	89.6525	89.6525	89.6525	89.6525
Upper Limit	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200	1200
Lower Limit	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300	300

$\bar{X}$	1200
$X = 623.79$	300

$\bar{R} = 27.4167$

UCL Xbar = 675.335

LCL Xbar = 572.2483

UCL Range = 89.6525

Table of Constants for Calculating Control Chart Limits				
Number of Values in Subgroups	X Bar	R		σ
(n)	A ₂	D ₃	D ₄	d ₂
2	1.88	.00	3.27	1.13
3	1.02	.00	2.57	1.69
4	.73	.00	2.28	2.06
5	.58	.00	2.11	2.33
6	.48	.00	2.00	2.53
7	.42	.08	1.92	2.70
8	.37	.14	1.86	2.85

Figure 3 Continued. Measurement System Evaluation Results

Operator bias is hinted when looking at the readings: Bill consistently measures higher than Dave. This slight shift is not a concern since this operator bias is 10 times more sensitive than the required results. The upper and lower limits on the control chart represent six sigma of the expected measurement error. Part-to-part variation is not quite as widely distributed when compared to the six sigma measurement error as would be desired. The six sigma measurement error is approximately 100 $\mu\text{in.}$, while total tolerancing on the laser scribe penetration parameter is approximately 1200 $\mu\text{in.}$ The conclusion is that the measurement system is acceptable for this application, but the narrow distribution of the parts selected for the study lead one to believe that it is marginal.

The range chart depicts good discrimination and a measurement process that is in control.

Analysis was performed for health hazards. Experimental scribing of each substrate was designed to duplicate material removal and scribe operation duration consistent with worst case exposures based on current production processes/schedules. Emission sampling was conducted by FM&T ES&H personnel during exposures.

An accuracy study was also conducted on the IBAS image analyzer (see Figure 4). Analysis for micro crack and spatter tendencies was accomplished during the characterization/optimization exercise using a scanning electron microscope (SEM).

Implementation of Experiment

Fabrication. Sample coupons were fabricated with surface finish and marking surface contours designed to eliminate marking inefficiencies caused by highly polished and/or severally contoured/radiused product (reflectivity and focal length distortion). Products exhibiting these characteristics are not common and may require additional experimentation to "fine tune" product-specific operating parameters.

The laser marking system (CE66801) in the FM&T Sheet Metal Fabrication and Assembly department was used in this characterization, optimization, and validation project. Operating parameters that are recommended in this report are system specific. A correlation study would be necessary to determine applicability to additional laser marking systems.

Five substrates were chosen for this exercise, based on current production schedules: beryllium copper, 304L and 21-6-9 stainless steel, titanium, and T6061-T6 aluminum. Four main effects set at two different levels with two center points made up the experimental design. The design of experiment entails 18 "treatments" for each substrate. The experimental design of "blocks" containing these 18 treatments for each of the substrates can be seen in Figure A-1 in the Appendix. The experiment was replicated in an attempt to capture as much process "noise" as possible. Five blocks, with 18 treatments each, were run for each of the various substrates. This equates to a total of 90 coupons generated for analysis for each substrate.

Instrument: IBAS Image Analyzer

Part/dimension/tolerance to be studied in related MSE: +/-0.0006

Taking Data:

1. A stage micrometer traceable to the NBS was used to validate accuracy. Standard 0.001014 in. was measured repeatedly.
2. The standard stage micrometer was measured 10 consecutive times and recorded below.

Values Measured

1. 0.001016 in.	6. 0.001035 in.
2. 0.001007 in.	7. 0.001039 in.
3. 0.001039 in.	8. 0.001039 in.
4. 0.001007 in.	9. 0.001039 in.
5. 0.001007 in.	10. 0.001067 in.

3. Average of 10 measurements: 0.001029 in.

4. Calculate
$$\frac{\text{Average Value} - \text{Master Value}}{\text{Tolerance}} (100) = \frac{0.001029 - 0.001014}{0.001200} (100) = 1.25\%$$

Conclusion: The IBAS image analyzer demonstrates acceptable accuracy for measuring laser scribe penetration. Error in the measurement system is 1.251%.

Figure 4. Accuracy Validation

Design of Experiment. Design of experiment was developed by team members. The process map and FMEA were used to prioritize actions directed toward ensuring that customer expectations are met. Controllable process variables needed to be identified and target ranges established. This would ensure optimization of component marking legibility and reduction of laser scribe impact on part function by minimizing penetration depth. Figure A-1 represents the initial experimental design for each of the five substrates. Originally a two level, four factor, full factorial experiment was designed with two runs established at center. The "vital few" process variables identified by expert team members were manipulated in the ranges specified in the matrix (Figure A-1). For example, in Figure A-1, page 1 (of 5 pages) depicts "feedrate" as a vital

process variable; the experimental operating limits are 0.15 inches per second to 4 inches per second. The other process variable columns are read similarly.

A specific DOE matrix was established for each of the five substrates. The experimental operating ranges developed by expert team inputs were established to achieve laser scribe results covering the entire spectrum of visually acceptable conditions.

Response variables or “product parameters” used to evaluate the laser scribe process are as follows:

Micro cracks	This condition is to be eliminated or minimized.
Spatters	This condition is to be eliminated or minimized.
Penetration	Penetration of the laser scribe into the substrate is to be minimized while still achieving legibility.
Legibility	For each experimental block, the test coupons were ranked from 1 to 18. One (1) designated the most legible test coupon while a ranking of 18 corresponded with the test coupon most difficult to read.
Emissions	Vapor emissions were sampled to determine if operators were being exposed to a metallic fume hazard.

Units of measure for the independent process variables are as follows:

Focal Length	Inches
Pulse	kHz/sec (frequency)
Feed Rate	Inches/second
Beam Current	Amperes

Nominal machine parameters (resulting in main effect limits) were established, for experimental purposes, based on expert knowledge provided by cognizant team members. The team membership is defined below:

Team Membership

PC&C Project Engineer (FM&T)	Andy Wannamaker
Process Engineering (FM&T)	Jack McGrath
Product Engineering (FM&T)	Bob VanCleave
Design Agency (LANL)	Lee Anderson
Manufacturing (FM&T)	Ray Wolfe
Mfg. Team Leader (FM&T)	Steve Penyock
Statistical Support (FM&T)	John Grice
ES&H (FM&T)	Larry Atkinson
SEM Laboratory (FM&T)	Bill Lepley
Metallography (FM&T)	Carl Boehning
Metallography (FM&T)	Bill Rowe
Planning Support (FM&T)	Joyce Anderson

Results. Analysis included a legibility ranking, laser scribe penetration depth determination, and SEM analysis for micro cracks and spatters. All analysis was performed by laboratory personnel. The results obtained from the initial experimental operating ranges can be seen pictorially in Figure A-2. See Summary Results Matrix, Figure A-3, for measurement results of response variables.

Vapors emitted during the process were sampled for health concerns by ES&H personnel. The vapors emitted during the process were not considered "significant metallic fume exposure." See the memorandum, Atkinson to Wannamaker, in the Appendix for ES&H sampling results.

The presence of splatters and micro cracks was substrate specific and could not be eliminated 100%. For example; the 21-6-9 stainless steel SEM analysis revealed no spatters, but some evidence of micro cracking can be seen at 1000X. No appreciable depth can be assigned to this condition. The material is firmly affixed and cannot be removed separately from the substrate with abrasive paper. The micro cracked surfaces abrade consistently with the parent material. Typical penetration samples and SEM photographs of cracks and spatters can be seen in Figure A-4. Also see Figure A-4 for documentation of micro cracks before and after abrade.

Statistical Analysis

Based on the initial wave of experimentation, statistical models were developed to predict the outcome of various "treatments" on each of the five substrates. The influence of the four main factors on three primary response variables is discussed in the following paragraph. Each substrate was analyzed separately in order to avoid generalizations about laser scribe process characterization.

For the 304L stainless steel substrate, the four main effects and their full factorial interactions were used in a statistical model to determine which has the most significant influences on the three response variables. These factors are identified in the normalized plot in Figure A-5. Average legibility, average penetration, and the log of the standard deviation of penetration (between block variability) were chosen as the response variables. The focal length appeared to have the largest influence on the amount of variability between the penetration values (**log of standard deviation of penetration**). The beam should be focused on the substrate surface or slightly above to minimize variability. When looking at the **average penetration** variable, feed rate, beam current, pulse rate, feed/pulse interaction, and feed/beam current interaction were the driving factors. In general, increases in feed rate and pulse will decrease laser penetration. When beam current is increased, the result will be increased penetration. **Legibility** was negatively influenced by increases in pulse and feed rate, while higher beam currents improved legibility. Focal length was relatively flat for the legibility and average penetration response variables.

The four main factors and their significant interactions used in the statistical models accounted for the response variables in the experiment at levels ranging from 96 to 99 percent. Very little noise was present in the models. A three-dimensional cube plot of the main effects allowed team members to derive optimum treatments. See Figure A-5 for additional examples of analytical data used on the 304L stainless steel substrate. Predicted outcomes could be determined using the statistical model. A confirmation run was then conducted to further validate the model. The recommended independent variable settings for the 304L substrate can be seen in Figure A-6.

The remaining substrates were analyzed in similar fashion, and the recommended process settings with predicted outcomes are listed in Figure A-5. Models for the 21-6-9 stainless steel, titanium, and aluminum accounted for 97 to 100% of the experimental results. The results on the aluminum substrate exhibit excessive variation. Additional experimentation outside the original main factor limits is required. Models for the beryllium copper substrate could only account for 80 to 93% of the experimental results obtained and may require further validation of the predicted outcomes.

To eliminate concerns about changes in laser scribing efficiencies after calibration/maintenance activity, a second confirmation run was conducted following extensive internal and external mirror realignment and lamp replacement. The results of the second confirmation runs were within the limits predicted.

Table 1 reports the (95% level) confirmed and predicted process distributions for the penetration variable when using optimized parameter settings.

Table 1. Process Distributions for Penetration Variable

Material	Penetration Avg. (microinches)	UCL/LCL (microinches)
21-6-9 Stainless Steel	544	832/256
304L Stainless Steel	569	860/278
Titanium	359	489/278
Beryllium Copper	362	527/197
T6061 T6 Aluminum	5000	2000/8000

Recommendations, Controls, and Conclusions

It is important to realize that this experimentation, run over time with multiple replications, may not capture all long term noise experienced by the laser scribe process. While confirmation runs were within the statistically predicted limits, it is difficult to determine if the data is part of the initial experiment distribution or separate distributions. Desired outcomes are well defined on the majority of the substrates, and margins for safety widely exceed process upper and lower control limits. As funding allows, it may be desirable to try and capture any longer term noise or special effects that could cause a shift in the response variable outcomes. The process will be monitored for this need.

Laser marking parameters recommended by this study should be utilized on current/future hardware processed on the ILM system, CE66801. Traveler documentation will mandate settings for specific critical process variables. Password control will be placed on validated laser scribe programs to prevent changes to critical parameters. A correlation exercise will be necessary to allow processing flexibility and utilization of additional marking systems. Operators have been instructed on the criticality of process parameters and the need for laser marker programs to be password protected to prevent process variation.

A matrix depicting optimum independent process variable settings for each of the five substrates can be seen in Figure A-6. These system parameters demonstrated good to excellent legibility while minimizing laser scribe penetration. Micro crack and spatter generation are minimal to nonexistent.

ACCOMPLISHMENTS

Experimentation was successful in identifying the main effects on the desired outcomes. Statistical models were accurate in predicting optimum parameter settings. The necessary controls have been implemented to ensure achievement of primary customer requirements on the stainless steel substrates.

APPENDIX

Experimental Design and Data

Rows	Dsnid	run	block	focal	pulse	feedrate	beamcurr	LensC	pulseC	feedrC	beamcurrC	CenterPt	Penave
1	10	1	1	0.05	2	0.2	20	1	-1	-1	1	0	811.8
2	11	2	1	-0.05	8	0.2	20	-1	1	-1	1	0	593.4
3	16	3	1	0.05	8	5	20	1	1	1	1	0	162.6
4	0	4	1	0	5	2.6	17.5	0	0	0	0	1	680.4
5	15	5	1	-0.05	8	5	20	-1	1	1	1	0	253.4
6	8	6	1	0.05	8	5	15	1	1	1	-1	0	348.2
7	7	7	1	-0.05	8	5	15	-1	1	1	-1	0	183.8
8	13	8	1	-0.05	2	5	20	-1	-1	1	1	0	225.6
9	4	9	1	0.05	8	0.2	15	1	1	-1	-1	0	266
10	6	10	1	0.05	2	5	15	1	-1	1	-1	0	191.8
11	3	11	1	-0.05	8	0.2	15	-1	1	-1	-1	0	188
12	0	12	1	0	5	2.6	17.5	0	0	0	0	1	558.4
13	14	13	1	0.05	2	5	20	1	-1	1	1	0	255.8
14	9	14	1	-0.05	2	0.2	20	-1	-1	-1	1	0	902.6
15	5	15	1	-0.05	2	5	15	-1	-1	1	-1	0	244.8
16	1	16	1	-0.05	2	0.2	15	-1	-1	-1	-1	0	649.6
17	2	17	1	0.05	2	0.2	15	1	-1	-1	-1	0	350
18	12	18	1	0.05	8	0.2	20	1	1	-1	1	0	586.4

Figure A-1. Initial Experimental Design Matrix -- 21-6-9 Stainless Steel

Rows	Dsnid	Run	Block	focal	Pulse	Feedrate	Beamcurr	lensc	pulsec	feedc	beamcc	tubec	CenterPt
1	10	1	1	0.05	2	0.2	20	1	-1	-1	1	1	0
2	11	2	1	-0.05	8	0.2	20	-1	1	-1	1	1	0
3	16	3	1	0.05	8	5	20	1	1	1	1	1	0
4	0	4	1	0	5	2.6	17.5	0	0	0	0	-1	1
5	15	5	1	-0.05	8	5	20	-1	1	1	1	-1	0
6	8	6	1	0.05	8	5	15	1	1	1	-1	-1	0
7	7	7	1	-0.05	8	5	15	-1	1	1	-1	1	0
8	13	8	1	-0.05	2	5	20	-1	-1	1	1	1	0
9	4	9	1	0.05	8	0.2	15	1	1	-1	-1	1	0
10	6	10	1	0.05	2	5	15	1	-1	1	-1	1	0
11	3	11	1	-0.05	8	0.2	15	-1	1	-1	-1	-1	0
12	0	12	1	0	5	2.6	17.5	0	0	0	0	1	1
13	14	13	1	0.05	2	5	20	1	-1	1	1	-1	0
14	9	14	1	-0.05	2	0.2	20	-1	-1	-1	1	-1	0
15	5	15	1	-0.05	2	5	15	-1	-1	1	-1	-1	0
16	1	16	1	-0.05	2	0.2	15	-1	-1	-1	-1	1	0
17	2	17	1	0.05	2	0.2	15	1	-1	-1	-1	-1	0
18	12	18	1	0.05	8	0.2	20	1	1	-1	1	-1	0

Figure A-1 Continued. Initial Experimental Design Matrix -- 304L Stainless Steel

Rows	Dsnid	run	block	focal	pulse	feedrate	beamcurr	LensC	pulseC	feedC	beamcurrC	CenterPt
1	10	1	1	0.05	2	2	18	1	-1	-1	1	0
2	11	2	1	-0	8	2	18	-1	1	-1	1	0
3	16	3	1	0.05	8	6	18	1	1	1	1	0
4	0	4	1	0	5	4	16.5	0	0	0	0	1
5	15	5	1	-0	8	6	18	-1	1	1	1	0
6	8	6	1	0.05	8	6	15	1	1	1	-1	0
7	7	7	1	-0	8	6	15	-1	1	1	-1	0
8	13	8	1	-0	2	6	18	-1	-1	1	1	0
9	4	9	1	0.05	8	2	15	1	1	-1	-1	0
10	6	10	1	0.05	2	6	15	1	-1	1	-1	0
11	3	11	1	-0	8	2	15	-1	1	-1	-1	0
12	0	12	1	0	5	4	16.5	0	0	0	0	1
13	14	13	1	0.05	2	6	18	1	-1	1	1	0
14	9	14	1	-0	2	2	18	-1	-1	-1	1	0
15	5	15	1	-0	2	6	15	-1	-1	1	-1	0
16	1	16	1	-0	2	2	15	-1	-1	-1	-1	0
17	2	17	1	0.05	2	2	15	1	-1	-1	-1	0
18	12	18	1	0.05	8	2	18	1	1	-1	1	0

Figure A-1 Continued. Initial Experimental Design Matrix -- Titanium

Rows	Dsnid	run	block	focal	pulse	feedrate	beamcurr	LensC	pulseC	feedrC	beamcurrC	CenterPt.	Penave
1	10	1	1	0.01	0.5	0.04	19	1	-1	-1	-1	0	282.2
2	11	2	1	-0	1	0.04	19	-1	1	-1	-1	0	338.4
3	16	3	1	0.01	1	0.15	20	1	1	1	1	0	355.2
4	0	4	1	0	0.75	0.1	20	0	0	0	1	1	417.8
5	15	5	1	-0	1	0.15	20	-1	1	1	1	0	317.6
6	8	6	1	0.01	1	0.15	19.5	1	1	1	0	0	272.2
7	7	7	1	-0	1	0.15	20	-1	1	1	1	0	295.8
8	13	8	1	-0	0.5	0.15	19	-1	-1	1	-1	0	293
9	4	9	1	0.01	1	0.04	19	1	1	-1	-1	0	237.8
10	6	10	1	0.01	0.5	0.15	20	1	-1	1	1	0	222.6
11	3	11	1	-0	1	0.04	19	-1	1	-1	-1	0	374
12	0	12	1	0	0.75	0.1	19.5	0	0	0	0	1	337
13	14	13	1	0.01	0.5	0.15	20	1	-1	1	1	0	259.2
14	9	14	1	-0	0.5	0.04	20	-1	-1	-1	1	0	347.4
15	5	15	1	-0	0.5	0.15	19	-1	-1	1	-1	0	278.4
16	1	16	1	-0	0.5	0.04	19	-1	-1	-1	-1	0	274.8
17	2	17	1	0.01	0.5	0.04	19	1	-1	-1	-1	0	220.6
18	12	18	1	0.01	1	0.04	20	1	1	-1	1	0	293

Figure A-1 Continued. Initial Experimental Design Matrix -- Beryllium Copper

Rows	Dsnid	run	block	focal	pulse	feedrate	beamcurr	LensC	pulseC	feedrC	beamcurrC	CenterPt.
1	10	1	1	0.05	2	0.15	20	1	-1	-1	1	0
2	11	2	1	-0	8	0.15	20	-1	1	-1	1	0
3	16	3	1	0.05	8	4	20	1	1	1	1	0
4	0	4	1	0	5	2.075	18	0	0	0	0	1
5	15	5	1	-0	8	4	20	-1	1	1	1	0
6	8	6	1	0.05	8	4	16	1	1	1	-1	0
7	7	7	1	-0	8	4	16	-1	1	1	-1	0
8	13	8	1	-0	2	4	20	-1	-1	1	1	0
9	4	9	1	0.05	8	0.15	16	1	1	-1	-1	0
10	6	10	1	0.05	2	4	16	1	-1	1	-1	0
11	3	11	1	-0	8	0.15	16	-1	1	-1	-1	0
12	0	12	1	0	5	2.075	18	0	0	0	0	1
13	14	13	1	0.05	2	4	20	1	-1	1	1	0
14	9	14	1	-0	2	0.15	20	-1	-1	-1	1	0
15	5	15	1	-0	2	4	16	-1	-1	1	-1	0
16	1	16	1	-0	2	0.15	16	-1	-1	-1	-1	0
17	2	17	1	0.05	2	0.15	16	1	-1	-1	-1	0
18	12	18	1	0.05	8	0.15	20	1	1	-1	1	0

Figure A-1 Continued. Initial Experimental Design Matrix -- Aluminum

304L S. S., Block 2

Figure A-2. Laser Scribed Test Coupons

2169 S. S., Block 1

Figure A-2 Continued. Laser Scribed Test Coupons

Titanium, Block 5

Figure A-2 Continued. Laser Scribed Test Coupons

Beryllium Copper, Block 4

Figure A-2 Continued. Laser Scribed Test Coupons

Aluminum, Block 5

Figure A-2 Continued. Laser Scribed Test Coupons

**Laser Marker D45 Design of Experiment
Penetration Data, 304L Stainless Steel
(microinches)**

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.
Run No.	Serial Number							
1	10	911	976	801	595	776	811.80	145.95
2	11	480	747	703	610	427	593.40	138.23
3	16	72	241	170	183	147	162.60	61.38
4	0(18)	650	1026	744	437	545	680.40	224.71
5	15	284	182	215	394	192	253.40	88.10
6	8	1098	179	170	124	170	348.20	419.70
7	7	101	184	198	207	229	183.80	49.09
8	13	215	266	275	170	202	225.60	44.25
9	4	320	146	343	168	353	266.00	100.52
10	6	180	214	202	125	238	191.80	42.82
11	3	107	164	238	225	206	188.00	53.22
12	0(12)	627	366	570	611	618	558.40	109.75
13	14	503	105	215	250	206	255.80	148.35
14	9	779	839	1018	858	1019	902.60	109.75
15	5	263	225	182	261	293	244.80	42.58
16	1	692	669	810	600	477	649.60	122.63
17	2	364	641	102		293	350.00	223.33
18	12	957	307	555	490	623	586.40	238.24

Figure A-3. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; 304 L Stainless Steel
Rank (1) good- (18) poor

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.	Penetration
Run No.	Serial Number								
1	10	5	3	5	3	4	4.00	1.00	812.00
2	11	1	2	2	2	3	2.00	0.71	593.00
3	16	14	13	13	11	13	12.80	1.10	163.00
4	0(18)	11	16	16	13	14	14.00	2.12	680.00
5	15	17	10	15	12	17	14.20	3.11	253.00
6	8	18	18	17	16	12	16.20	2.49	348.00
7	7	16	17	18	15	18	16.80	1.30	184.00
8	13	9	11	12	8	10	10.00	1.58	225.00
9	4	8	7	8	7	7	7.40	0.55	266.00
10	6	13	9	14	14	16	13.20	2.59	192.00
11	3	6	6	7	6	8	6.60	0.89	188.00
12	0(12)	10	15	10	17	15	13.40	3.21	558.00
13	14	12	14	9	9	11	11.00	2.12	255.00
14	9	3	4	3	4	2	3.20	0.84	903.00
15	5	15	12	11	10	9	11.40	2.30	245.00
16	1	7	8	6	5	5	6.20	1.30	650.00
17	2	4	5	4		6	4.75	0.96	350.00
18	12	2	1	1	1	1	1.20	0.45	586.00
Top seven coupons for legibility ranking with coinciding depth									
18	12	2	1	1	1	1	1.20	0.45	586.00
2	11	1	2	2	2	3	2.00	0.71	593.00
14	9	3	4	3	4	2	3.20	0.84	903.00
1	10	5	3	5	3	4	4.00	1.00	812.00
17	2	4	5	4		6	4.75	0.96	350.00
16	1	7	8	6	5	5	6.20	1.30	650.00
11	3	6	6	7	6	8	6.60	0.89	188.00

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; 304 L Stainless Steel
Rank (1) good- (18) poor
Penetration in microinches

Run No.	Serial Number	Legibility	Penetration	Cracks	Spatters	Hazard
		Average	Average			
1	10	4	812.00	NO	NO	NO
2	11	2	593.00	NO	NO	NO
3	16	12.8	163.00	NO	NO	NO
4	0(18)	14	680.00	NO	NO	NO
5	15	14.2	253.00	NO	YES	NO
6	8	16.2	348.00	NO	NO	NO
7	7	16.8	184.00	NO	NO	NO
8	13	10	225.00	NO	YES	NO
9	4	7.4	266.00	NO	NO	NO
10	6	13.2	192.00	NO	NO	NO
11	3	6.6	188.00	NO	NO	NO
12	0(12)	13.4	558.00	NO	NO	NO
13	14	11	255.00	NO	NO	NO
14	9	3.2	903.00	NO	NO	NO
15	5	11.4	245.00	NO	YES	NO
16	1	6.2	650.00	NO	YES	NO
17	2	4.75	350.00	NO	NO	NO
18	12	1.2	586.00	NO	NO	NO
Top seven coupons for legibility ranking						
18	12	1.2	586.00	NO	NO	NO
2	11	2	593.00	NO	NO	NO
14	9	3.2	903.00	NO	NO	NO
1	10	4	812.00	NO	NO	NO
17	2	4.75	350.00	NO	NO	NO
16	1	6.2	650.00	NO	YES	NO
9	4	7.4	266.00	NO	NO	NO

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

**Laser Marker D45 Design of Experiment
Penetration Data, 21-6-9 Stainless Steel
(micro inches)**

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.
Run No.	Serial Number							
1	10	3485	1365	1336	1728	1346	1852.00	927.57
2	11	911	692	1206	1264	980	1010.60	231.71
3	16	330	604	147	160	179	284.00	193.45
4	0(18)	1346	1786	940	614	1673	1271.80	493.37
5	15	293	307	316	431	463	362.00	78.84
6	8	192	192	147	179	189	179.80	19.10
7	7	234	225	225	202	248	226.80	16.75
8	13	412	271	225	480	183	314.20	126.58
9	4	124	133	225	160	192	166.80	41.96
10	6	192	183	261	202	156	198.80	38.75
11	3	238	353	372	366	408	347.40	64.47
12	0(17)	709	1262	316	1254	238	755.80	491.98
13	14	280	211	192	284	192	231.80	46.50
14	9	2558	3128	2899	2007	2705	2659.40	422.78
15	5	353	303	316	284	192	289.60	60.11
16	1	1565	2749	2806	2787	1988	2379.00	570.34
17	2	252	229	614	297	293	337.00	157.44
18	12	656	545	614	532	532	575.80	56.30

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; 21-6-9 Stainless Steel
Rank (1) good- (18) poor

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.	Penetration
Run No.	Serial Number								
1	10	3	2	1	2	5	2.60	1.52	1852.00
2	11	2	3	3	3	2	2.60	0.55	1010.00
3	16	13	11	11	15	12	12.40	1.67	284.00
4	0(18)	10	15	9	12	11	11.40	2.30	1271.00
5	15	12	12	15	10	17	13.20	2.77	362.00
6	8	18	17	13	13	18	15.80	2.59	179.00
7	7	15	16	14	18	16	15.80	1.48	226.00
8	13	14	10	18	16	14	14.40	2.97	314.00
9	4	9	5	5	4	4	5.40	2.07	167.00
10	6	16	14	16	11	15	14.40	2.07	199.00
11	3	7	9	7	8	8	7.80	0.84	347.00
12	0(12)	11	13	8	14	9	11.00	2.55	756.00
13	14	8	7	6	6	10	7.40	1.67	231.00
14	9	5	4	4	5	3	4.20	0.84	2659.00
15	5	17	18	17	17	13	16.40	1.95	289.00
16	1	4	6	10	7	6	6.60	2.19	2379.00
17	2	2	2	12	9	7	6.40	4.39	337.00
18	12	1	1	2	1	1	1.20	0.45	575.00
Top seven coupons for legibility ranking									
18	12	1	1	2	1	1	1.20	0.45	575.00
1	10	3	2	1	2	5	2.60	1.52	1852.00
2	11	2	3	3	3	2	2.60	0.55	1010.00
14	9	5	4	4	5	3	4.20	0.84	2659.00
9	4	9	5	5	4	4	5.40	2.07	167.00
17	2	2	2	12	9	7	6.40	4.39	337.00
16	1	4	6	10	7	6	6.60	2.19	2379.00

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; 21-6-9 Stainless Steel
Rank (1) good- (18) poor
Penetration in microinches

		Legibility	Penetration	Cracks	Spatters	Hazard
Run No.	Serial Number	Average	Average			
1	10	2.6	1852.00	NO	NO	NO
2	11	2.6	1010.00	NO	YES	NO
3	16	12.4	284.00	NO	YES	NO
4	0(18)	11.4	1271.00	NO	NO	NO
5	15	13.2	362.00	NO	YES	NO
6	8	15.8	179.00	NO	NO	NO
7	7	15.8	226.00	NO	NO	NO
8	13	14.4	314.00	NO	YES	NO
9	4	5.4	167.00	YES	NO	NO
10	6	14.4	198.00	NO	NO	NO
11	3	7.8	347.00	NO	NO	NO
12	0(12)	11	756.00	YES	NO	NO
13	14	7.4	231.00	NO	NO	NO
14	9	4.2	2659.00	NO	YES	NO
15	5	16.4	289.00	NO	YES	NO
16	1	6.6	2379.00	NO	YES	NO
17	2	6.4	337.00	YES	NO	NO
18	12	1.2	575.00	NO	NO	NO
Top seven coupons for legibility ranking						
18	12	1.2	575.00	NO	NO	NO
1	10	2.6	1852.00	NO	NO	NO
2	11	2.6	1010.00	NO	YES	NO
14	9	4.2	2659.00	NO	YES	NO
9	4	5.4	167.00	YES	NO	NO
17	2	6.4	337.00	YES	NO	NO
16	1	6.6	2379.00	NO	YES	NO

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

**Laser Marker D45 Design of Experiment
Penetration Data, Titanium
(microinches)**

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.
Run No.	Serial Number							
1	10	192	275	335	339	271	282.40	59.85
2	11	170	499	663	545	581	491.60	189.54
3	16	160	170	192	225	179	185.20	25.17
4	0(4)	183	156	192	215	372	223.60	85.61
5	15	256	170	192	225	179	204.40	35.60
6	8	114	202	261	124	147	169.60	61.41
7	7	435	137	147	160	206	217.00	124.69
8	13	124	275	261	248	238	229.20	60.43
9	4	124	160	170	225	170	169.80	36.20
10	6	124	156	215	124	225	168.80	48.66
11	3	160	137	170	385	160	202.40	102.79
12	0(12)	183	183	290	183	160	199.80	51.40
13	14	215	114	147	170	192	167.60	39.20
14	9	376	398	389	343	353	371.80	23.36
15	5	206	238	248	215	261	233.60	22.83
16	1	412	398	412	490	404	423.20	37.80
17	2	229	307	225	147	225	226.60	56.59
18	12	124	147	192	353	160	195.20	91.57

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Titanium
Rank (1) good- (18) poor

Run No.	Serial Number	Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.	Penetration
1	10	6	2	1	1	2	2.40	2.07	282.00
2	11	7	11	4	6	6	6.80	2.59	491.00
3	16	13	7	13	9	13	11.00	2.83	185.00
4	0(18)	12	10	11	11	9	10.60	1.14	223.00
5	15	8	9	14	16	8	11.00	3.74	233.00
6	8	16	19	18	15	15	16.60	1.82	169.00
7	7	7	16	15	18	17	14.60	4.39	217.00
8	13	5	6	6	8	3	5.60	1.82	229.00
9	4	9	14	17	14	14	13.60	2.88	170.00
10	6	17	17	9	13	11	13.40	3.58	169.00
11	3	18	15	16	10	16	15.00	3.00	202.00
12	0(12)	15	11	10	17	12	13.00	2.92	199.00
13	14	4	8	3	4	7	5.20	2.17	168.00
14	9	2	3	5	7	5	4.40	1.95	372.00
15	5	10	18	12	5	18	12.60	5.55	233.00
16	1	11	12	2	3	10	7.60	4.72	423.00
17	2	14	13	7	12	4	10.00	4.30	227.00
18	12	3	4	8	2	1	3.60	2.70	195.00

Top seven coupons for legibility ranking

1	10	6	2	1	1	2	2.40	2.07	282.00
18	12	3	4	8	2	1	3.60	2.70	195.00
14	9	2	3	5	7	5	4.40	1.95	372.00
13	14	4	8	3	4	7	5.20	2.17	168.00
8	13	5	6	6	8	3	5.60	1.82	229.00
2	11	7	11	4	6	6	6.80	2.59	491.00
16	1	11	12	2	3	10	7.60	4.72	423.00

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Titanium
Rank (1) good- (18) poor
Penetration in microinches

		Legibility	Penetration	Cracks	Spatters	Hazard
Run No.	Serial Number	Average	Average			
1	10	2.4	282.00	NO	NO	NO
2	11	6.8	491.00	NO	YES	NO
3	16	11	185.00	NO	NO	NO
4	0(4)	10.6	223.00	NO	NO	NO
5	15	11	233.00	NO	NO	NO
6	8	16.6	169.00	NO	NO	NO
7	7	14.6	217.00	NO	NO	NO
8	13	5.6	229.00	NO	YES	NO
9	4	13.6	169.00	NO	NO	NO
10	6	13.4	168.00	NO	NO	NO
11	3	15	202.00	NO	NO	NO
12	0(12)	13	199.00	NO	NO	NO
13	14	5.2	167.00	NO	NO	NO
14	9	4.4	371.00	NO	YES	NO
15	5	12.6	233.00	NO	YES	NO
16	1	7.6	423.00	NO	YES	NO
17	2	10	226.00	NO	NO	NO
18	12	3.6	195.00	NO	NO	NO
Top seven coupons for legibility ranking						
1	10	2.4	282.00	NO	YES	NO
18	12	3.6	195.00	NO	NO	NO
14	9	4.4	371.00	NO	YES	NO
13	14	5.2	167.00	NO	NO	NO
8	13	5.6	229.00	NO	YES	NO
2	11	6.8	491.00	NO	YES	NO
16	1	7.6	423.00	NO	YES	NO

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

**Laser Marker D45 Design of Experiment
Penetration Data, Beryllium Copper
(microinches)**

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.
Run No.	Serial Number							
1	10	339	261	362	211	238	282.20	65.32
2	11	376	284	330	372	330	338.40	37.56
3	16	389	261	398	330	398	355.20	59.82
4	0(4)	215	431	682	431	330	417.80	172.47
5	15	389	307	275	320	297	317.60	43.17
6	8	238	206	307	362	248	272.20	62.07
7	7	366	183	215	330	385	295.80	91.25
8	13	421	261	284	206	293	293.00	79.15
9	4	200	206	160	339	284	237.80	72.23
10	6	238	183	284	229	179	222.60	43.35
11	3	398	385	275	404	408	374.00	56.02
12	0(12)	421	421	229	376	238	337.00	96.30
13	14	284	275	238	238	261	259.20	21.02
14	9	376	431	261	421	248	347.40	87.42
15	5	160	275	431	206	320	278.40	105.22
16	1	307	192	147	398	330	274.80	103.02
17	2	238	238	183	261	183	220.60	35.59
18	12	275	316	261	398	215	293.00	68.89

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Beryllium Copper
Rank (1) good- (18) poor

Run No.	Serial Number	Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.	Penetration
1	10	14	12	14	13	15	13.60	1.14	282.20
2	11	2	3	6	3	2	3.20	1.64	338.40
3	16	7	5	4	6	3	5.00	1.58	355.20
4	0(18)	1	2	1	8	8	4.00	3.67	417.80
5	15	3	4	7	2	4	4.00	1.87	317.60
6	8	12	13	3	10	14	10.40	4.39	272.20
7	7	4	8	10	7	7	7.20	2.17	295.80
8	13	6	9	13	14	6	9.60	3.78	293.00
9	4	10	11	8	9	10	9.60	1.14	237.80
10	6	13	17	16	15	13	14.80	1.79	222.60
11	3	8	6	5	4	10	6.60	2.41	374.00
12	0(12)	11	10	11	5	1	7.60	4.45	337.00
13	14	9	7	12	12	9	9.80	2.17	259.20
14	9	15	14	15	11	11	13.20	2.05	347.40
15	5	17	15	9	16	12	13.80	3.27	278.40
16	1	18	18	18	17	17	17.60	0.55	274.80
17	2	16	16	17	18	16	16.60	0.89	220.60
18	12	5	1	2	1	5	2.80	2.05	293.00
Top seven coupons for legibility ranking									
18	12	5	1	2	1	5	2.80	2.05	293.00
2	11	2	3	6	3	2	3.20	1.64	338.40
4	0(18)	1	2	1	8	8	4.00	3.67	417.80
5	15	3	4	7	2	4	4.00	1.87	317.60
3	16	7	5	4	6	3	5.00	1.58	355.20
11	3	8	6	5	4	10	6.60	2.41	374.00
7	7	4	8	10	7	7	7.20	2.17	295.80

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Beryllium Copper
Rank (1) good- (18) poor
Penetration in microinches

Run No.	Serial Number	Legibility Average	Penetration Average	Cracks	Spatters	Hazard
1	10	13.6	282.20	NO	NO	need
2	11	3.2	338.40	NO	YES	NO
3	16	5	355.20	NO	YES	NO
4	0(18)	4	417.80	NO	YES	NO
5	15	4	317.60	NO	YES	NO
6	8	10.4	272.20	NO	YES	NO
7	7	7.2	295.60	NO	YES	NO
8	13	9.6	293.00	NO	YES	NO
9	4	9.6	237.80	NO	YES	NO
10	6	14.8	222.60	NO	YES	NO
11	3	6.6	374.00	NO	YES	NO
12	0(12)	7.6	337.00	NO	YES	NO
13	14	9.8	259.20	NO	YES	NO
14	9	13.2	347.40	NO	YES	NO
15	5	13.8	278.40	NO	YES	NO
16	1	17.6	274.80	NO	YES	NO
17	2	16.6	220.60	NO	YES	NO
18	12	2.8	293.00	NO	YES	NO

Top seven coupons for legibility ranking

18	12	2.80	337.00	NO	YES	NO
2	11	3.20	223.00	NO	YES	NO
4	0(18)	4.00	200.00	NO	YES	NO
5	15	4.00	278.00	NO	YES	NO
3	16	5.00	374.00	NO	YES	NO
11	3	6.60	338.00	NO	YES	NO
7	7	7.20	296.00	NO	YES	NO

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

**Laser Marker D45 Design of Experiment
Penetration Data, Aluminum
(microinches)**

		Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.
Run No.	Serial Number							
1	10	114	7536	8055	8956	7460	6424.20	3577.61
2	11	385	454	353	147	522	372.20	141.76
3	16	192	307	261	307	137	240.80	74.71
4	0(4)	297	225	389	192	238	268.20	77.47
5	15	467	366	229	238	330	326.00	98.30
6	8	114	179	238	376	3729	927.20	1569.24
7	7	96	275	238	215	353	235.40	93.88
8	13	398	587	587	1946	509	805.40	642.30
9	4	261	284	284	229	206	252.80	34.54
10	6	170	156	376	192	435	265.80	129.86
11	3	330	284	284	229	206	266.60	49.27
12	0(12)	160	147	229	192	398	225.20	101.66
13	14	499	454	252	147	366	343.60	144.81
14	9	7034	8987	9326	8567	10497	8882.20	1258.05
15	5	1003	297	532	421	490	548.60	269.15
16	1	7080	5921	4766	3997	7353	5823.40	1447.59
17	2	170	1401	252	320	343	497.20	509.71
18	12	192	316	376	444	147	295.00	124.21

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Aluminum T6
Rank (1) good- (18) poor

Run No.	Serial Number	Block 1	Block 2	Block 3	Block 4	Block 5	Average	Std. Dev.	Penetration
1	10	6	5	5	1	5	4.40	1.95	6424.00
2	11	8	8	1	2	11	6.00	4.30	372.00
3	16	15	16	15	15	9	14.00	2.83	240.00
4	0(18)	12	12	13	11	12	12.00	0.71	268.00
5	15	13	9	7	9	8	9.20	2.28	326.00
6	8	18	18	18	18	18	18.00	0.00	927.00
7	7	18	13	18	18	14	16.20	2.49	235.00
8	13	2	2	4	4	2	2.80	1.10	805.00
9	4	16	17	18	18	15	16.80	1.30	252.00
10	6	9	11	14	14	13	12.20	2.17	265.00
11	3	14	15	6	13	17	13.00	4.18	267.00
12	0(12)	11	14	9	10	10	10.80	1.92	225.00
13	14	3	3	2	5	3	3.20	1.10	343.00
14	9	4	4	12	7	6	6.60	3.29	8882.00
15	5	7	7	3	3	4	4.80	2.05	549.00
16	1	1	1	11	6	1	4.00	4.47	5823.00
17	2	5	6	10	8	7	7.20	1.92	497.00
18	12	10	10	8	12	16	11.20	3.03	295.00

Top seven coupons for legibility ranking

8	13	2	2	4	4	2	2.80	1.10	293.00
13	14	3	3	2	5	3	3.20	1.10	259.20
16	1	1	1	11	6	1	4.00	4.47	274.80
1	10	6	5	5	1	5	4.40	1.95	282.20
15	5	7	7	3	3	4	4.80	2.05	278.40
2	11	8	8	1	2	11	6.00	4.30	338.40
14	9	4	4	12	7	6	6.60	3.29	347.40

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Laser Marker D45 Design of Experiment
Legibility Data; Aluminum T6
Rank (1) good- (18) poor
Penetration in microinches

Run No.	Serial Number	Legibility	Penetration	Cracks	Spatters	Hazard
		Average	Average			
1	10	4.4	6424.00	NO	NO	NO
2	11	6	372.00	NO	NO	NO
3	16	14	241.00	NO	NO	NO
4	0(4)	12	268.00	NO	NO	NO
5	15	9.2	326.00	NO	NO	NO
6	8	18	927.00	NO	NO	NO
7	7	16.2	235.00	NO	NO	NO
8	13	2.8	805.00	NO	NO	NO
9	4	16.8	253.00	NO	NO	NO
10	6	12.2	265.00	NO	YES	NO
11	3	13	267.00	NO	NO	NO
12	0(12)	10.8	225.00	NO	NO	NO
13	14	3.2	343.00	NO	NO	NO
14	9	6.6	8882.00	NO	NO	NO
15	5	4.8	549.00	NO	YES	NO
16	1	4	5823.00	NO	YES	NO
17	2	7.2	497.00	NO	NO	NO
18	12	11.2	295.00	NO	NO	NO

Top seven coupons for legibility ranking

2	11	2.8	372.00	NO	NO	NO
8	13	3.2	805.00	NO	NO	NO
13	14	4	343.00	NO	NO	NO
1	10	4.4	6424.00	NO	NO	NO
14	9	4.8	8882.00	NO	NO	NO
15	5	6	549.00	NO	YES	NO
16	1	6.6	5823.00	NO	YES	NO

Figure A-3 Continued. Summary Matrix: Measurement Results of Response Variables

Date: August 22, 1995

To: [REDACTED]

From: L. B. Atkinson, D/SH1, BC30

Subject: Chemical Air Sampling During Laser Marking Operations In D/45

As part of an evaluation of airborne metal fume generation during laser marking operations in D/45, Industrial Hygiene performed air sampling during laser marking operations. Various metal and metallic alloys were used (in coupon format) during a set of standardized marking operations. During these standardized tests, various power levels and scroll speeds were utilized. In each sampling session, three air samples were taken simultaneously. One was taken on the laser operator. Another sample was drawn from inside the unvented laser cabinet. The third sample was taken on the workstation located about 12 feet from the laser cabinet.

The results are as follows:

Aluminum

No detection of aluminum in the laser operator's breathing zone or from the area sample taken on the workstation desk. A small concentration of aluminum fume was found within the laser cabinet.

Copper-Beryllium Alloy

No detection of beryllium in the laser operator's breathing zone. The laser operator's breathing zone contained a small concentration of copper. A small concentration of airborne copper and beryllium was found within the laser cabinet. The area near the workstation desk contained no detectable copper or beryllium fume.

Stainless Steel

Low level detection of both nickel (0.001 ug/m^3) and chromium (0.002 ug/m^3) in the breathing zone of the operator. There was detection of the fumes of nickel (0.039 ug/m^3) and chromium (0.01 ug/m^3) in the sample taken inside the laser enclosure. The sample taken at the workstation contained a measurable concentration of chromium but no nickel ($<0.0008 \text{ mg/m}^3$). The Occupational Safety and Health Administration has designated a permissible exposure limit of 0.5 mg/m^3 for chromium and 1 mg/m^3 for nickel.

A. L. Wannamaker

Page 2

None of the sampling detected concentrations even approaching regulatory limits. The highest concentrations of metals were found within the laser cabinet. As a matter of good safety procedure, associates should not thrust their heads into the enclosure immediately after significant laser marking usage. Based on the available sampling data, associates will not be exposed to significant metallic fume if reasonable safety procedures are followed.

Please post this memorandum on the D/45 bulletin board so that associates can have access to the information provided. Contact me at extension 5896 if you have any questions or comments.

A handwritten signature in cursive script that reads "Larry Atkinson". The signature is written in dark ink and is positioned above the typed name and title.

L. B. Atkinson
Staff Industrial Hygienist

LBA/wp

cc: S. J. Penyock, D/MA1, FG43
D. J. Haynes, D/MM1, FN31

21-6-9 S. S., Block 4, S/N 15, 500X, Approx. 300 μ in.

304L S. S., Block 1, S/N 0-4, 500X, Approx. 600 μ in.

Figure A-4. SEM Photographs of Cracks and Spatters

304L S. S., Block 1, S/N 12, 500X, Approx. 1000 μ in.

21-6-9 S. S., Block 4, S/N 10, 500X, Approx. 1700 μ in.

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

21-6-9 S. S., Block 4, S/N 0-4, 500X, Approx. 600 μ in.

21-6-9 S. S., Block 4, S/N 9, 500X, Approx. 2000 μ in.

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

21-6-9 S. S., Block 4, S/N 1, 500X, Approx. 2700 μ in.

Aluminum, Block 3, S/N 10, 250X, Approx. 8000 μ in.

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

304L S. S. Microcracks, Abraded With 600 Grit Paper

BEFORE

AFTER

Figure A-4 Continued. SEM Photographs of Cracks-and Spatters

21-6-9 S. S. Microcracks, Abraded With 600 Grit Paper

BEFORE

AFTER

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

21-6-9 S. S. Microcracks, Abraded With 600 Grit Paper

BEFORE

AFTER

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

304L S. S. Laser Scribe, Abraded With 600 Grit Paper

BEFORE

AFTER

Figure A-4 Continued. SEM Photographs of Cracks and Spatters

The prediction profile demonstrates the relationship between the main effects and the response variables.

Figure A-5. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

Effect Screening

Response: Penave

The estimates are correlated and need a transformation.

The estimates have different variances and need scaling.

Transformed Parameter Estimates

Length PSE

1.6092475

Normal Plot

Heavy line is length's PSE.

Light line is RMSE.

Figure A-5 Continued. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

Screening Fit

Penetration Average					
Summary of Fit					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Model	4	575603.35	143901	4.7659	
Error	13	392520.51	30194	Prob>F	
C Total	17	968123.86		0.0138	
Lack of Fit					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Lack of Fit	12	385078.51	32089.9	4.3120	
Pure Error	1	7442.00	7442.0	Prob>F	
Total Error	13	392520.51		0.3612	
				Max RSq	
				0.9923	
Parameter Estimates					
Effect Test					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
pulseC	1	1	68932.50	2.2830	0.1547
feedrC	1	1	384958.20	12.7495	0.0034
beamcurrC	1	1	117203.52	3.8817	0.0705
LensC	1	1	4509.12	0.1493	0.7054

Screening fit will help discern the applicability of the model (MAXRSq) and reveal the significance of the independent variables on the responses (F ratio).

Figure A-5 Continued. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

Screening Fit

Log Penetration Standard Deviation					
Summary of Fit					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Model	4	0.5348325	0.133708	1.8573	
Error	13	0.9358668	0.071990	Prob>F	
C Total	17	1.4706994		0.1782	
Lack of Fit					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Lack of Fit	12	0.88743856	0.073953	1.5271	
Pure Error	1	0.04842828	0.048428	Prob>F	
Total Error	13	0.93586684		0.5659	
				Max RSq	
				0.9671	
Parameter Estimates					
Effect Test					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
pulseC	1	1	0.02049719	0.2847	0.6026
feedrC	1	1	0.19428454	2.6988	0.1244
beamcurrC	1	1	0.01767396	0.2455	0.6285
LensC	1	1	0.30237684	4.2003	0.0612

Figure A-5 Continued. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

Screening Fit

Legibility Average					
Summary of Fit					
Analysis of Variance					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Model	4	356.20062	89.0502	16.2633	
Error	13	71.18174	5.4755	Prob>F	
C Total	17	427.38236		0.0001	
Lack of Fit					
Source	DF	Sum of Squares	Mean Square	F Ratio	
Lack of Fit	12	71.001736	5.91681	32.8712	
Pure Error	1	0.180000	0.18000	Prob>F	
Total Error	13	71.181736		0.1356	
				Max RSq	
				0.9996	
Parameter Estimates					
Effect Test					
Source	Nparm	DF	Sum of Squares	F Ratio	Prob>F
pulseC	1	1	11.30641	2.0649	0.1744
feedrC	1	1	308.44141	56.3310	0.0000
beamcurrC	1	1	36.45141	6.6572	0.0229
LensC	1	1	0.00141	0.0003	0.9875

Figure A-5 Continued. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

This cube analysis reveals the impact of the main effects on average penetration, average legibility, and the log penetration standard deviation.

Figure A-5 Continued. Plots of Prediction Profile, Effect Screening, Screening Fit, and Cube Plot

Laser Marker Operating Parameter Settings

Marker CE# 66801 Area D45 ILM system									
Variable process inputs	Beam current	Line width	Feed rate	Pulse freq	Char. Ht	Focal lgth	Average	LCL 95%	UCL 95%
Material									
304L stn stl	17.5 amps	.005"	.2 in/sec	5KHz/sec	.120"	0	569 u"	278 u"	860 u"
21-6-9 stn stl	20.0 amps.	.005"	.5 in/sec	8KHz/sec.	.120"	0	544 u"	256 u"	832 u"
BeCu	20.0 amps	.005"	.05 in/sec	1KHz/sec.	.120"	0	362 u"	197 u"	527 u"
Titanium	20.0 amps	.005"	2.0 in/sec	2KHz/sec	.120"	0	359 u"	228 u"	489 u"
Aluminum T6***	18.0 amps	.005"	.2 in/sec	2KHz/sec	.120"	0	5000 u"	2000 u"	8000 u"

*** Experimental limits must be shifted and ranges reduced to minimize variability on this substrate.

Figure A-6. Recommended Variable Settings for Experimental Substrates