INEL-94/00136
CONF-9509182--7

Surface Preparation via Grit-Blasting for Thermal Spraying

D. J. Varacalle, Jr., L. B. Lundberg, R. S. Hartley
Idaho National Engineering Laboratory
Idaho Falls, Idaho 83415

J. Walker
Walker Sandblasting
Idaho Falls, Idaho 83401

W. L. Riggs II
TubalCain Company
Loveland, Ohio

RECEIVED
OCT 27 1995
OSTI

Abstract

The major reason for grit blasting for thermal spray applications is to ensure a strong mechanical bond between the substrate and the coating by the enhanced roughening of the substrate material. This study presents five statistically designed experiments that were accomplished to investigate the grit blasting process. The experiments were conducted using a Box statistical design of experiment (SDE) approach. A substantial range of grit blasting parameters and their effect on the resultant substrate roughness were investigated, including grit type, pressure, working distance, and exposure time. The substrates were characterized for surface characteristics using image analysis. These attributes are correlated with the changes in operating parameters. Optimized process parameters for the two machines used in this study as predicted by the SDE analysis are presented.

THE GRIT BLAST PROCESS INVOLVES the spraying of abrasive particles against the surfaces of parts or products to remove contaminants and/or condition the surfaces for subsequent finish operations. Thermal spray processes are being used in up to 46 industries for a variety of applications. For these applications, the capability of the processes to achieve maximum bond strength is crucial to the success of any particular application. Thermal spray coatings rely primarily upon mechanical bonding to the substrate. Thus, it is critical that the substrate be properly prepared to ensure maximum coating bond strength. Surface cleanliness and roughness are the most critical factors. It is especially important that the substrate remains uncontaminated by lubricants or oils. The substrate should be cleaned following grit blasting to remove residual dust by either rinsing with a solvent or air drying using clean, dry compressed air. It is important that the prepared surface is coated as soon as possible after preparation to prevent surface oxidation or contamination, which cause coating failures.

Practical grit size ranges are -10 +30 mesh (i.e., coarse), -14 +40 mesh (i.e., medium), and -30 + 80 mesh (i.e., fine). Typically, coarse grit is used for coatings exceeding 10 mils for best adherence; medium grit is used for smoother finishes of coatings less than 10 mils with fair adherence; and fine grit grit is used for the smoothest finishes on coatings less than 10 mils to be used in the as-sprayed condition. Because surface roughness is primarily the result of grit particle size, the selection of the grit size is determined by the required coating thickness. Surface roughness can also be varied by air pressure. This factor should be considered on an individual basis for each combination of grit size, type, and substrate material.

Alumina, silica sand, crushed steel, chilled iron, copper slag, and silicon carbide are often used as abrasive grit. Ceramics are commonly used on large exterior structures such as bridges, towers, and piping where recovery of the grit is impractical. Metal grit, obtained commercially in hardnesses to 65 HRC, is used on hardened steels.

Consideration should be given to the substrate materials in the selection of grit types. Traces of residual grit may adversely affect some coatings. Chemical compatibility in the finished coating system must be considered. Alumina, sand, and especially silicon carbide may embed in softer metals such as aluminum, copper, and their alloys. For these metals, lower air pressures are typically used to minimize embedding.

Grit blasting air pressure varies from 210 to 620 kPa (30 to 90 psi), with typical working distances of 50 to 150 mm (2 to 6 in.). Grit blast nozzle openings are generally 6 to 10 mm (0.25 to 0.375 in.) in diameter. The blasting angle to the substrate should be about or slightly less than 90°.

Statistical design of experiments (SDE) has been rigorously developed for over 60 years by numerous scientists, including Sir Ronald Fisher(1). The main reason for designing an experiment statistically is to obtain unambiguous results at a minimum cost. Thus, SDE methods are important tools to an engineer wishing to achieve the best possible design for a product. As such, SDE strategies are rapidly becoming invaluable resources in many industries (2). These experimental designs represent a plan for constructively changing the input parameters in order to determine their effect on the attributes of the product. A variety of SDE strategies are available to obtain statistical information within the selected test matrix.

This paper presents a design of experiment methodology for the grit blast process. Use of this methodology results in optimized surface roughness, and corresponding coating bond strength, by obtaining a scientific understanding of the physical mechanisms involved in the preparation of substrates for thermal spraying.

Experimental Procedure

Two devices were used for the abrasive blasting experiments: an Econoline RA 36-1 Blast Cabinet (3) and a Clemco 100-lb capacity pressurized-pot blaster(4).

The Econoline cabinet is rectangular and is a self-contained, recycling, sealed glove box design. It is capable of blasting small pieces, up to 30 inches in length. The abrasive hopper, which is located below the work table, holds between 25 to 50 lbs of blasting material. The spray gun consists of a 25-scfm carbide nozzle and a 25-scfm air jet housed in a large bronze gun body. The blasting media is drawn into the gun through a siphon tube connected to the base of the gun's pistol grip. A pressure regulator on the exterior of the cabinet allows the operator to regulate air supply pressure from 10 to 120 psia. An external dust collector sweeps and filters the air in the cabinet to improve visibility during blasting operations.

The Clemco blast machine is a much larger device, capable of blasting very large pieces or structures. The device is a nonrecycling, pressurized-pot design. The device consists of a large, upright, cylindrical pressure-tight hopper with a funnel base. Two lines are connected to the hopper. The air pressure supply line is connected to the side of the hopper and pressurizes the hopper and directs air flow down to the mixing connection. The other line connects to the bottom of the hopper and meters the abrasive media into the air stream. The flow out of the mixing connection is directed through a 50-foot long, 1.5-inch inside diameter blasting hose. The blasting media is then accelerated and directed to the working surface of the piece through a 5/16-inch venturi nozzle.

Three types of abrasive blast media were used for the experiments. These included 35-mesh copper slag, 35-mesh silica sand, and 60-mesh alumina grit.

Box standard design of experiments (5) were used to optimize the process parameters for the grit blast equipment. This statistical analysis was accomplished with the use of the Design-Ease software (6). The designs evaluated the effect of the processing variables on the quantitatively measured responses. The design of experiment approach is ideal because it statistically delineates the impact of each process parameter on the measured characteristics across all combinations of the other parameters. The parameters being optimized in the grit blast studies included working distance, exposure time, blast media, and pressure.

Once classical experiments were conducted to ascertain important process parameters, full-factorial experiments were conducted to determine the parameter space for optimization of surface preparation. Five major studies were conducted. Experiments WC1 through WC15 and WS1 through WS15 used Clemco equipment. Experiments IS1 through IS15, IC1 through IC15, and IA1 through IA15 used Econoline equipment. All five studies used a 2-level, 3-variable (i.e., working distance, exposure time, pressure) full-factorial design, as illustrated in Table 1. Each variable has two levels selected to band around the centerpoint settings.

The process parameters used for the experiments are illustrated in Table 2. The substrates used for the studies were low carbon steel. The primary gas was air. All manipulation of the devices was done manually.

Characterization and SDE Results

Cross-sections of the surfaces of the target samples grit blasted with the various parameters were prepared for metallographic examination. Representative microstructures for the cross-sections of surfaces grit blasted produced by the two different process systems are presented in Figures 1 and 2. The surfaces produced by grit blasting with the Econoline system appear to be relatively free from embedded grit or surface scale particles, while foreign particles, like those indicated in Figure 2, are frequently seen embedded in the surfaces produced with the Clemco system. The attributes evaluated were average rough-

Table 1. Full-factorial design of experiment.

Exp. (#)	Spray dist. (level)	Pressure (level)	Expos. time (level)
1	-1	-1	-1
2	+1	-1	-1
3	-1	+1	-1
4	+1	+1	-1
5	-1	-1	+1
6	+1	-1	+1
7	-1	+1	+1
8	+1	+1	+1
9	0	0	0
10	0	0	0
11	0	0	0
12	0	-1	-1
13	0	+1	-1
14	0	-1	+1
15	0	+1	+1

Table 2. Experiment process parameters.

Clemco Experiments: WC1-WC15 (copper slag grit) and WS1-WS15 (silica grit)

Variable	Units	-1 level	+1 level
A. Working distance	inches	12	16
B. Pressure	psia	80	100
C. Exposure time	seconds	4	2

Econoline Experiments: IC1-IC15 (copper slag grit), IS1-IS15 (silica grit), and IA1 through IA15 (alumina grit)

Variable	Units	-1 level	+1 level
A. Working distance	inches	2	4
B. Pressure	psia	60	90
C. Exposure time	seconds	5	10

ness, maximum peak-to-peak height, normalized line length, and the surface area enhancement factor (SAEF).

The attributes were measured using image analysis techniques on the two-dimensional image of each surface cross-section. The measurements were made on images seen through a Nikon Epiphot metallograph at a magnification of 200 ×, using a Dapple Image Analyzer. Data were collected to calculate the roughness, the maximum peak heights (measured from the valley floors), and the trace length. Twenty frames per sample were processed. Surface roughness values were calculated per ANSI standard B46.1, which is an average deviation from the mean line of elevation through the surface asperities. The trace or fiber length of each surface cross-section was also measured relative to a chord length connecting the starting and ending points of the surface tracing line. The ratio of the squares of the fiber and chord lengths is a measure of the surface area enhancement produced by the gritblasting. Characterization results are presented in Table 3.

Once the experiments were conducted and the characterization was completed, the data were then analyzed with the Design-Ease program. Full-factorial plans involve running all combinations of conditions of the independent variables. This allows evaluation of all three factors and all of their interactions. Effects analysis was conducted for the surface responses using Design-Ease and is shown in Table 3.

The effects analysis indicates the Clemco equipment (experiments WC and WS) roughens the substrates more than the Econoline equipment (experiments IA, IC, and IS), with larger amplitudes, and slightly larger normalized line lengths. Copper slag grit resulted in more surface modification than the other grits for the Econoline machine, while it can be argued there is little difference between the silica and copper grits used in the Clemco machine. SAEFs for the grit blasted surfaces produced by the Clemco system range from 1.1 to 4.3, while the SAEFs produced by the Econoline system ranged from 1.3 to 3.3, indicating the enhanced surface finish with the Clemco machine.

When studying the process parameters and finding their effects to be significant, one is interested in finding conditions (levels of the parameters) that lead to a particular response, usually a maximum or a minimum. Graphical procedures based on normal probability plots were then used for the fac-

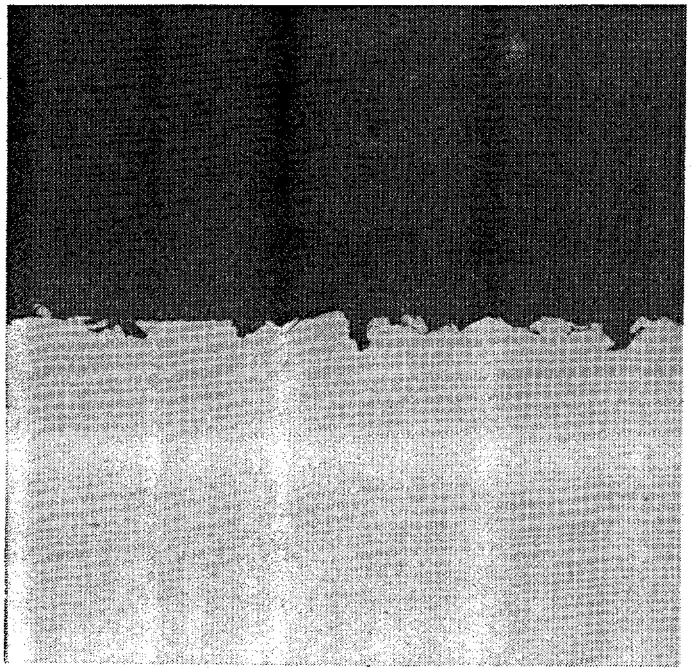

Figure 1. Cross-section of a typical surface grit blasted with alumina using the Econoline machine (sample IA03).

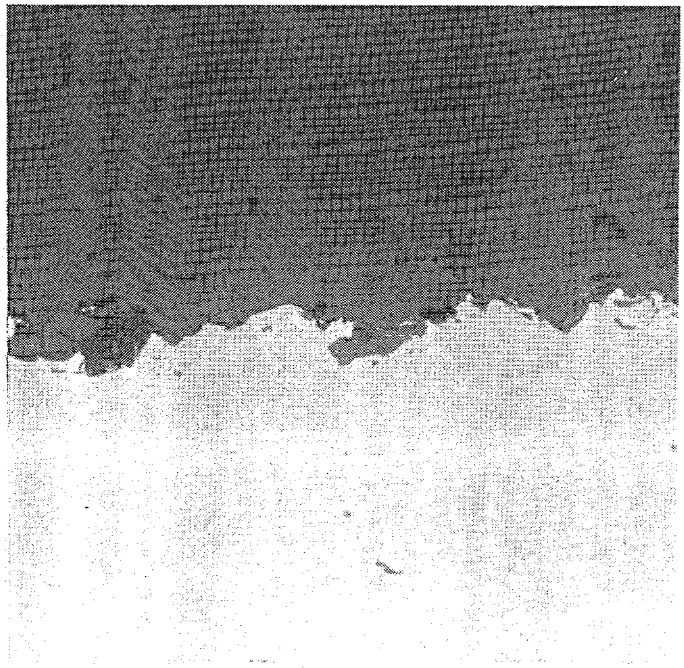

Figure 2. Cross-section of a typical surface grit blasted with copper slag using the Clemco machine (sample WC11).

Table 3. Results of the effects analysis (roughness and amplitude in microns, normalized line length non-dim).

				<--Effect from Level 1 to Level 2--->		
Study	Variable	Range	Average	Working Distance	Pressure	Expos. Time
IS	Roughness	4.9-9.1	7.4	-0.2	1.5	-0.2
	Amplitude	18.7-42.2	32.7	-1.6	7.1	-3.9
	Norm. Len.	1.2-1.6	1.36	-0.26	0.16	0.07
	SAEF	1.3-2.6	1.87	-0.75	0.45	0.20
IA	Roughness	6.2-11.6	8.6	-0.1	-0.2	1.9
	Amplitude	29.6-45.4	37.5	-2.4	-1.3	9.0
	Norm. Len.	1.2-1.6	1.29	-0.01	-0.01	0.12
	SAEF	1.3-2.4	1.67	-0.00	-0.00	0.33
IC	Roughness	7.4-12.8	9.9	0.6	-0.2	0.7
	Amplitude	34.2-54.7	41.6	3.3	2.1	0.6
	Norm. Len.	1.1-1.8	1.35	0.08	-0.09	-0.06
	SAEF	1.3-3.3	1.87	0.20	-0.31	-0.18
WC	Roughness	7.4-13.3	10.6	-2.7	2.0	-0.04
	Amplitude	31.5-61.1	46.4	-13.8	5.8	3.1
	Norm. Len.	1.1-1.7	1.36	-0.2	0.1	-0.09
	SAEF	1.1-3.0	1.87	-0.53	0.31	-0.31
WS	Roughness	6.9-19.4	10.1	-2.7	-3.0	-1.0
	Amplitude	28.6-73.6	42.2	-6.5	-13.7	-4.8
	Norm. Len.	1.0-2.1	1.43	-0.08	-0.3	-0.3
	SAEF	1.1-4.3	2.14	-0.30	-1.0	-0.76

torial cases to choose an appropriate model for each response. Once the effects analysis was completed, the ANOVA (analysis of variance) calculations were then conducted for each response. For example, the A, B, A*B model for roughness for study IS (SiO2 grit, Econoline machine) yielded an F value (comparison of the treatment variance with the error variance) of 11.5 and a probability value of 0.14% (probability that the model terms are null). Also, the coefficient of variation (CV) was 7.1%, indicating that the error was relatively small. These values indicate that this model was robust for the resistance attribute. This yielded the regression equation (A and B use the coded variables = -1 to +1):

$$\text{Roughness (Study IS)} = 7.14 - 0.085*A + 0.61*B - 0.79*A*B \quad \text{(Eq. 1)}$$

where A = working distance, B = primary pressure, and C = exposure time.

The residual analysis indicated there were no problems in the data. The cube plot of the predicted (Eq. 1) values for the roughness was constructed. Figure 3 illustrates the values for the combinations of the -1 and +1 levels of the three selected variables. As is obvious, the maximum roughness for the SiO2 grit using the Econoline machine is obtained at the -1 value of working distance (2 in.) and exposure time (5 sec.), and the +1 level for pressure (90 psia).

The optimization methodology then examined the influence of the parameters on the measured response from the effects analysis. An influence variable (I%) was then calculated to indicate which process parameters are the most influential on the attribute of interest. This variable I% indicates the influence for both the main responses and their interactions. Then, using the levels also obtained from the effects analysis and weighting the roughness attributes in the total design, a surface finish can be obtained. Table 4 illustrates the results of the Design-Ease analysis for the 5 studies. As illustrated in the table, the surface finish should possess high values of SAEF, normalized line length, roughness, and amplitude in order of priority. This was a significant amount of variance for the surface attributes for the Econoline machine for the 3 grit materials used. It is interesting to note that interaction effects overwhelm the main effects for all four surface attributes for the IC (copper slag) study. Working distance and pressure had little to no effect on the surface conditions for the IA (alumina) study, while longer exposure time significantly increased all four surface attributes. In the IS (silica) study, the surface characteristics were relatively insensitive to exposure time and working distance for the roughness and amplitude, while the pressure was a significant contributor to modifying all four surface characteristics.

The WS (silica) study for the Clemco machine indicated significant interaction effects. All four surface attributes indicate the optimum process parameters are at the lower level of working distance (12 inches), exposure time (4 seconds), and pressure (80 psia). This correlates with the characterization analysis for this study. The WC (copper slag) study indicated

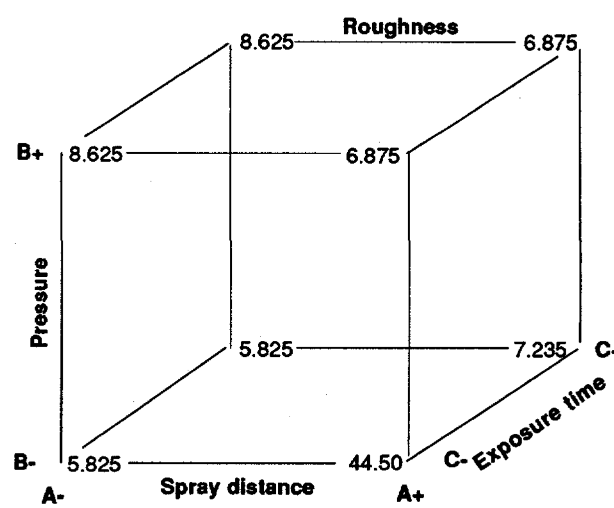

Figure 3. Cube plot for roughness (silica grit, Econoline machine).

Table 4. Results of the design-ease analysis.

Processing factor: Desired attribute	Working fist. %l/level	Pressure %l/level	Expos. fime %l/level
IS Study			
1 High SAEF	67.8/-1	24.3/+1	5.0/+1
2 High Norm. Line Length	66.0/-1	26.6/+1	4.8/+1
3 High Roughness	1.0/-1	40.5/+1	1.0/-1
4 High Amplitude	2.0/-1	41.6/+1	12.5/-1
IA Study			
1 High SAEF	0.0/-1	0.0/-1	21.3/+1
2 High Norm. Line Length	0.2/-1	0.4/-1	36.0/+1
3 High Roughness	0.1/-1	0.3/-1	39.7/+1
4 High Amplitude	3.3/-1	1.0/-1	45.6/+1
IC Study			
1 High SAEF	3.7/+1	8.7/-1	3.1/-1
2 High Norm. Line Length	4.5/+1	7.1/-1	3.0/-1
3 High Roughness	7.8/+1	0.5/-1	9.6/+1
4 High Amplitude	22.7/+1	9.3/+1	0.9/+1
WC Study			
1 High SAEF	47.5/-1	16.2/+1	16.2/-1
2 High Norm. Line Length	55.5/-1	15.8/+1	13.3/-1
3 High Roughness	53.2/-1	27.2+1	0.0/-1
4 High Amplitude	61.7/-1	10.7/+1	3.2/+1
WS Study			
1 High SAEF	2.3/-1	25.4/-1	14.5/-1
2 High Norm. Line Length	1.4/-1	27.0/-1	20.3/-1
3 High Roughness	14.4/-1	18.0/-1	2.1/-1
4 High Amplitude	6.3/-1	27.8/-1	3.5/-1

a strong dependence on working distance with a secondary influence from the system pressure. All four surface attributes indicate the optimum process parameters are at the lower level for working distance and exposure time, and the maximum pressure (100 psia).

SUMMARY AND CONCLUSIONS

An experimental study of the grit blasting process has been presented. Major parameters investigated included working distance, pressure, exposure time, and grit media for two grit blast machines.

The effects analysis indicates the Clemco equipment roughened the substrates more than the Econoline equipment. Copper slag grit resulted in more surface modification than the other grits for the Econoline machine, while it can be argued there is little difference between the silica and copper grits used in the Clemco machine. SAEFs for the grit blasted surfaces produced by the Clemco system range from 1.1 to 4.3, while the SAEF's produced by the Econoline system ranged from 1.3 to 3.3, indicating the enhanced surface finish with the Clemco machine.

Trends were indicated by the statistical effects analysis for the factorial models. In general, the interaction effects dominated the Econoline machine statistics, while the Clemco machine was dominated by working distance and pressure. The corresponding ANOVA calculations for each study yielded regression equations for all of the surface responses, which allowed the optimization of the final parameter settings for the grit blast machines for each grit media.

The objective of this work was to initiate work to optimize the bond strength for twin-wire electric arc sprayed aluminum coatings. After baseline data are generated on the process parameters that influence the surface characteristics, the performance relationship between the surface morphology and the coating must be quantitatively evaluated using a similar design of experiment approach. From this methodology, blasting parameters can be adjusted, optimized, and confirmed. A realistic specification can be made for the coating as sprayed, and ultimately, the specification will be transferred back to the control parameters only.

Future work will emphasize coating bond strength studies using full-factorial statistically designed experiments.

ACKNOWLEDGMENTS

The work described in this paper was supported by the U.S. Department of Energy, Assistant Secretary for Defense, under DOE Contract No. DE-AC07-94ID13223.

REFERENCES

1. R. A. Fisher, The Design of Experiments, Oliver and Boyd, Edinburgh, 1935.

2. C. G. Pfeifer, Planning Efficient and Effective Experiments, Mechanical Engineering, May 1988, pp. 35-39.

3. Econoline Manual RA 36-1, Econoline Abrasive Products Division, Grand Haven, MI 49417.

4. Clemco Abrasive Blast Equipment Selection Guide, Clemco Industries, Washington, MO 63090.

5. G. E. P. Box, W. G. Hunter, and J. S. Hunter, Statistics for Experimenters, Wiley, 1978.

6. P. Whitcomb et al, Design-Ease, Version 2.0, Stat-Ease Incorporated, 2021 E. Hennepin, 191, Minneapolis, MN 55413. Design-Ease is a registered trademark of Stat-Ease Incorporated.

DISCLAIMER