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Examination of a Grit-Blasting Process for Thermal Spraying Using Statistical Methods

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An experimental study was conducted to develop an understanding of how the grit blasting process, prior to plasma spray coating, affects various properties of the substrate and coatings. A statistical design of experiment approach was used and the results were analyzed using both the linear regression method and average response of factors calculations. The following process variables were studied: grit size (20, 36, 54), blasting pressure (20, 35, 50 psi), blasting duration (4, 6, 8 passes), blasting distance (4, 6 in.), and blasting angle (45°, 90°). Properties such as bond strength, grit contamination, surface roughness, and substrate distortion were evaluated and correlated to the process variables. Based on multiple linear regression results, it was shown that the bond strength can be improved by increasing all of the parameters within the range studied here. No relationship between the surface roughness and bond strength was observed. Grit contamination is mostly influenced by grit size, blasting pressure, and number of blasting passes. The average response method provided indications to the direction of modifying the required properties as a function of process variables. While the average response method agreed mostly with the linear regression predication, some differences are further discussed in the study.

Keywords average response curve, bond strength, grit blasting, linear regression, plasma spray, surface roughness

1. Introduction

Thermal spraying is a generic term for processes in which solid particles are fed into a flame and projected onto a substrate to form a coating. Plasma spraying is considered to be the most flexible thermal spray process as it can deliver sufficient energy to melt any material. The plasma spray system uses a direct current (dc) voltage applied to a cathode in the spray gun to create an unstable plasma. Extremely high temperatures, up to 16,000 °C, can be created when the plasma recombines to the gaseous state. When a coating material in powder form is introduced into the gas, it is melted and propelled toward the target substrate on which it is deposited (Ref 1). Thermal spraying is used to manufacture metallic and ceramic coatings for purposes including wear, corrosion, and thermal barrier requirements.

It is known that the adhesion of thermally sprayed coatings depends critically on the condition of the surface before spraying and that pretreatment to provide surface roughening is essential (Ref 2). Grit blasting has been used in virtually all thermal spray processes and it is very crucial that a desirable surface condition is produced prior to coating to guarantee an acceptable bond strength and interface microstructure, and to minimize the residual stress. The grit blasting process uses abrasive particles propelled by compressed air onto the surface of parts to be coated. This produces a roughened surface for subsequent coating processes while also achieving removal of surface contaminants. Thermal spray coatings obtain their bonding to the substrate primarily through mechanical keying action (Ref 3); though some chemical bonding is also present due to the thermal effect during spraying and subsequent heat treatment. Grit blasting involves adjusting the following parameters to achieve the optimum outcome: grit size and distribution, compressed air pressure, spray distance, number of passes, spraying angles, and nozzle diameters.

There have been several studies conducted in the past to examine how the bond strength/coating adhesion can be affected by the grit blasting process (Ref 4-7) with a majority of the emphasis placed on roughness of the surface. Roughening of surfaces using grit blasting, as a method to improve adhesion, is a controversial topic in the literature. Surface roughness after blasting is the subject of many studies (Ref 5–8). In general, a coarser grit size (lower grit size number) produces rougher surfaces (Ref 4). In one study, it was found that the surface roughness increased linearly with the grit size and was not affected by blasting distance and angle. The blasting time increased the roughness initially, and then the degree of roughness reached a plateau (Ref 8). A fractal analysis, measurement for surface roughness, showed that a blasting angle of 75° (with #20 Alumina grit) produced adhesion strength and fractal dimension to their maximum value (Ref 9).

While the roughness was observed to contribute to coating bond strength, it is a secondary effect. In other words, the blasting process produced certain characteristics on the substrate, including surface roughness, leading to subsequent bond strength.

The objectives of this study were to examine how various process variables affect the properties of the blasted substrate in a synergetic manner and provide a method to optimize the grit blasting process to achieve the best industrial standard.

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Table 1 Experimental variables and levels

Variable/ factor	Description	Levels		
A	Grit size number	$A_0 = 20$	$A_{1/2} = 36$	$A_1 = 54$
B	Blasting pressure, psi	$B_0 = 20$	$B_{1/2} = 35$	$B_1 = 50$
C	No. of blasting passes	$C_0 = 4$	$C_{1/2} = 6$	$C_1 = 8$
D	Working distance, in.	$D_0 = 4''$	…	$D_1 = 6''$
E	Blasting angle	$D_0 = 45°$	…	$D_1 = 90°$

2. Experimental

2.1 Design of Experiment

The effects of five variables/factors, namely grit size (*A*), blasting pressure (*B*), number of blasting passes (*C*), working distance (*D*), and blasting angle (*E*), were examined in this investigation. The factor levels are given in Table 1. These variables are referred to as independent variables in the later sections when the linear regression method is introduced.

Factors for grit size (*A*), blasting pressure (*B*) and number of passes (*C*) were chosen to run at three levels, while other factors for working distance (*D*) and blasting angle (*E*) were at two levels. A full factorial design was carried out to examine all five factors in two levels, resulting in a total of 32 (2^5) experiments. The additional center points for grit size (*A*), blasting pressure (*B*), and number of passes (*C*) resulted in 16 extra experimental trials, for a total of 48. The factor and level combinations are given in the test matrix (Table 2).

2.2 Materials

The substrate material for this study was Hastelloy X in both sheet and bar forms. The sheet material was used to evaluate the surface roughness, distortion, and grit contamination. The bar material was machined into buttons and used to evaluate the bond strength after various blasting processes.

The grit material used was fused Al_2O_3 (alumina) with grit size ranging from 20 to 54. The grit material was controlled and specified by ANSI B74.12 with only new material being used throughout this experimental study. Note that a larger grit size number corresponds to smaller grit particles. A constant nozzle size (1/4 in.) was used for all the tests conducted.

2.3 Testing Method

There are various methods available to evaluate the grit blasted surface. For example, to measure the surface profile, a fractal method (Ref 9) can provide a more complete picture than a roughness test. Similarly, a hole drilling method resulted in a better understanding of the residual stress generated compared with distortion measurements (Ref 8). However, one of the purposes of this study is to provide the industry with a simple method to evaluate the blasting process. Therefore, all the tests conducted in this study were designed based on the possibility of industry adopting and extending the methodology to other types of equipment and substrates. Furthermore, because the current study was focused on the effects of grit blasting processes relative to generating useful information to industrial users, the details of failure or adhesion mechanism(s) is not discussed in this article.

2.3.1 Bond Strength. A Co-based alloy (Amdry 316, Troy, MI) was used to coat the test buttons for bond strength/pull tests after grit blasting. To ensure that the contamination was kept to a minimum, the coating operation was carried out within 2 h after blasting. A Metco 3MB gun (Westbury, NY) was used to perform the coating operation and the power supply settings were: 45-55 V, 490-510 A, No. 30 flow meter reading, and powder flow rate of 6-7 lb/h. The spray distance was kept at 2.0-2.5 in. Other plasma spray settings were adjusted according to the material's data sheet (Amdry 316) specifically for the Metco plasma spray system. The pull test fixture was set up according to ASTM C633-79 (Ref 10).

Three pull test buttons were prepared for each condition. The buttons were bonded to the test fixtures using FM 1000 adhesive (Cytec Engineered Materials, West Paterson, NJ), which was qualified to have minimum bond strength of 11,000 psi. However, bond strength as high as 13,000 psi for FM 1000 was commonly seen. The coated samples were vapor degreased and dried using compressed nitrogen prior to adhesive bonding. Because the bond strength test was carried out over an extended period of time, process control coupons were used and cured at the same time as the coated buttons being bonded to the text fixture. The bond strength of the control coupons was typically in the range of 11,000-13,000 psi.

Furthermore, the fracture surfaces were examined after all pull tests, primarily for indications of failure occurring in the adhesive or between the adhesive and coating bond line. If such failure was observed, the bond strength value would be considered suspect and therefore discarded. Because the number of meaningful bond strength values ranged between 1 and 3, it was determined that only the maximum meaningful strength should be used for this study.

2.3.2 Surface Roughness. A portable SR-16B profilometer (Maradith Products) was used to measure the roughness of the as-grit-blasted surfaces on flat coupons made of sheet material. The difference between the highest peak and deepest undercut was measured. The profilometer was equipped with a 5 μm diamond and calibrated prior to each measurement. Three readings were taken, and the average of these readings is presented in Table 3.

2.3.3 Surface Grit Contamination Measurement. The surface contamination as a result of grit blasting was determined using an optical microscope, at a magnification of 40×, by counting the total number of embedded particles. The values given in Table 3 are the total number of particles found in an area of 28 mm^2 (0.043 $in.^2$).

2.3.4 Distortion. Distortion that occurred during blasting due to residual stresses was evaluated by measuring the distance (*d*) between the highest point and the lowest points (as shown in Fig. 1) of the distorted coupons (2.54 × 7.62 cm) over a length of 7.62 cm, then normalizing it by subtracting the thickness of the coupon prior to the blasting operation (d_0) as distortion $\delta = d - d_0$.

3. Experimental Results

3.1 Linear Regression Method

Statistical analysis software (SCC) was used to analyze the correlation between the independent variables and the depen-

Table 2 Test matrix

Set 1			Set 2		
$A_0B_0C_0D_0E_0$	$A_0B_0C_1D_1E_0$	$A_{1/2}B_{1/2}C_{1/2}D_0E_0$	$A_1B_0C_0D_0E_0$	$A_1B_0C_1D_1E_0$	$A_{1/2}B_{1/2}C_{1/2}D_0E_0$
$A_1B_1C_0D_0E_0$	$A_0B_0C_1D_0E_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_0$	$A_0B_1C_0D_0E_0$	$A_1B_0C_1D_0E_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_0$
$A_1B_0C_1D_0E_0$	$A_0B_0C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_1$	$A_0B_0C_1D_0E_0$	$A_1B_0C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_0$
$A_1B_0C_0D_1E_0$	$A_1B_1C_1D_1E_0$	$\mathrm{A}_{1/2}B_{1/2}C_{1/2}D_1E_0$	$A_0B_0C_0D_1E_0$	$A_0B_1C_1D_1E_0$	$A_{1/2}B_{1/2}C_{1/2}D_1E_0$
$A_1B_0C_0D_0E_1$	$A_1B_1C_1D_0E_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_1$	$A_0B_0C_0D_0E_1$	$A_0B_1C_1D_0D_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_1$
$A_0B_1C_1D_0E_0$	$A_1B_1C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_1$	$A_1B_1C_1D_0E_0$	$A_0B_1C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_0E_1$
$A_0B_1C_0D_1E_0$	$A_0B_0C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_0$	$A_1B_1C_0D_1E_0$	$A_0B_0C_0D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_1$
$A_0B_1C_0D_0E_1$	$A_1B_0C_1D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_1$	$A_1B_1C_0D_0E_1$	$A_1B_1C_1D_1E_1$	$A_{1/2}B_{1/2}C_{1/2}D_1E_1$

Table 3 Summary of parameter settings and measured results (dependent variables)

I.D.	Grit size No.	Blasting pressure, psi	No. of pass	Working distance, in.	Angle, degree	Roughness	Max. distortion, δ	Contamination, M	Max. bond strength (σ), psi	OEC
1	20	20	4	4	90	341	161	18	5,900	43.25
2	20	20	8	6	90	320	107	30	9,010	57.90
3	20	20	8	4	45	323	106	21	6,800	50.58
4	20	20	4	6	45	246	52	21	12,400	86.32
5	20	50	8	4	90	327	294	20	9,800	54.81
6	20	50	4	6	90	379	218	23	8,400	50.53
7	20	50	8	6	45	407	198	20	10,500	65.65
8	20	50	4	4	45	410	125	27	9,900	63.41
9	36	35	6	4	90	266	84	24	7,320	53.38
10	36	35	6	4	90	280	83	43	7,800	45.22
11	36	35	6	6	45	229	53	31	7,500	52.58
12	36	35	6	6	90	289	86	38	7,600	46.75
13	36	35	6	4	45	243	34	38	10,400	66.41
14	36	35	6	4	45	259	45	33	5,100	38.33
15	36	35	6	6	90	229	86	32	8,000	52.49
16	36	35	6	6	45	276	137	21	8,300	56.90
17	54	50	4	4	90	205	68	15	12,200	87.50
18	54	20	8	4	90	124	28	2	8,617	77.46
19	54	20	4	6	90	125	22	6	9,420	80.15
20	54	50	8	6	90	231	103	5	9,800	77.11
21	54	20	4	4	45	117	14	10	6,800	63.49
22	54	50	8	4	45	200	54	6	9,700	79.46
23	54	50	4	6	45	198	54	11	8,680	70.77
24	54	20	8	6	45	123	15	6	8,000	72.56
25	54	20	4	4	90	117	18	7	10,980	88.74
26	54	20	8	6	90	128	15	7	7,000	66.29
27	54	20	8	4	45	130	17	8	12,400	96.32
28	54	20	4	6	45	130	16	3	10,300	87.32
29	54	50	8	4	90	223	110	12	10,000	73.71
30	54	50	4	6	90	204	55	17	9,600	72.47
31	54	50	4	4	45	192	50	17	9,700	73.40
32	54	50	8	6	45	211	49	8	11,100	86.64
33	36	35	6	4	90	290	100	31	11,100	69.72
34	36	35	6	4	90	272	55	25	9,900	69.57
35	36	35	6	6	90	253	78	43	10,260	59.59
36	36	35	6	6	90	245	53	54	9,300	49.56
37	36	35	6	4	45	256	36	30	9,000	62.91
38	36	35	6	4	45	260	44	32	6,100	44.67
39	36	35	6	6	45	234	45	24	8,600	63.45
40	36	35	6	6	45	252	48	41	7,100	44.89
41	20	50	4	4	90	411	182	31	11,100	63.87
42	20	20	8	4	90	334	155	22	12,000	76.11
43	20	20	4	6	90	318	78	18	3,620	36.20
44	20	50	8	6	90	362	232	24	5,500	32.44
45	20	20	4	4	45	301	59	17	6,330	53.56
46	20	50	8	4	45	289	218	17	10,386	65.31
47	20	50	4	6	45	402	139	27	10,400	65.26
48	20	20	8	6	45	326	61	21	9,840	71.10

dent variables in a multiple linear regression manner. The linear regression gives the general relationship between several independent variables and a dependent variable. A line in two-dimensional, or two-variable, space is defined by the equation Y = a + bX, where the constants a and b are referred to as the intercept and the slope of the regression. In the multivariant case, when there is more than one independent variable, the regression line cannot be visualized in two-dimensional space but can be

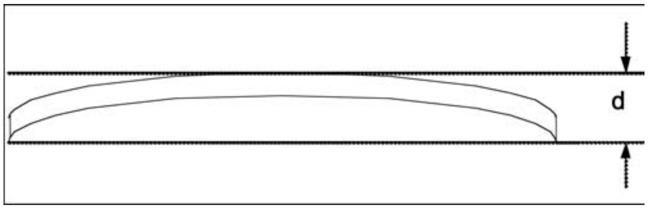

Fig. 1 Distortion $\delta = d - d_0$ (where d_0 is the material's thickness)

computed. In general, multiple regression procedures will estimate a linear equation of the form:

$$Y = \mathrm{a} + \mathrm{b}_1X_1 + \mathrm{b}_2X_2 + \mathrm{b}_3X_3 + \mathrm{b}_4X_4 + \ldots + \mathrm{b}_nX_n \qquad \text{(Eq 1)}$$

3.2 Statistical Significance: p Level

The statistical significance of results is an estimated measure of the degree to which it is true. The value of the *p* level represents a decreasing index of the reliability of result. The higher the *p* level, the less one can believe that the observed relationship between the variables in the sample is a reliable indicator of the relationship between the respective variables in the population. For example, a *p* level of 0.05 indicates there is a 5% probability the relationship between the variables found in the samples is not related.

3.3 R Square

The degree to which two or more variables are related to the dependent variables is expressed in the correlation coefficient *R*. In multiple regressions, *R* can assume values between 0 and 1. If there is no relationship between the *X* and *Y* variables, the ratio of the residual variability of the *Y* variable to the original variance is equal to 1.0. If *X* and *Y* are perfectly related, there is no residual variance, and the ratio of variance would be 0. One minus this ratio is referred to as an *R* square, and this value can be interpreted in the following manner: if the *R* square is 0.4, the variability of *Y* values around the regression line is (1 − 0.4) times the original variance; i.e., only 40% of the original variability can be explained.

3.4 Average Response Curves

The average response method (Ref 11, 12) provides a means of evaluating the effects of five variables/factors and level settings against each evaluation/dependent variable, such as bond strength, surface roughness, grit contamination, and distortion, individually or combined as a whole. The response curves show trends in dependent variables with respect to raising or lowering level settings of independent variables or they can indicate that a specific parameter has been optimized. If all the evaluations/dependent variables are combined into an overall evaluation criterion using predetermined weighting factors, an average response calculation can predict an optimal combination of all parameter settings. This is especially important for cases where a fractional factorial design of experiments method has been used because the average response calculation can predict independent variable/factor level combinations that were not tested in the experimental trials.

A spreadsheet was used to calculate the average response

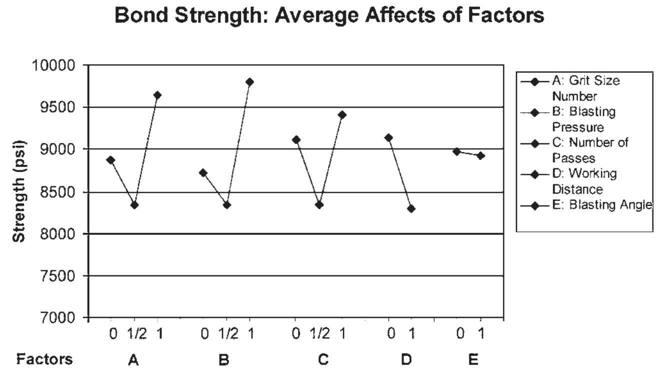

Fig. 2 Average effects of factors on bond strength

graphs. To analyze the effects of independent variables on the individual evaluation (strength, contamination, distortion, and roughness), the design matrix was simplified to low, medium, and high level settings represented by the numbers 1, 2, and 3, respectively. The average affect of grit size (factor A) at level 1 was then found by summing all the results that correspond to trials that contain the setting A1 and dividing by the number of occurrences of that setting. This process applies to all factor and level combinations. Once all the average response values were calculated, they were plotted against the independent variable setting values producing average response graphs, as shown in Fig. 2-5.

To combine the results for contamination, distortion, and bond strength into single numerical results for each trial, the following calculation was performed for the results of every experimental trial, giving an overall evaluation criterion or overall evaluation criterion (OEC) value:

$$\mathrm{OEC_i} = 50\left(\frac{\sigma_\mathrm{i} - \mathrm{MIN}_\sigma}{\mathrm{MAX}_\sigma - \mathrm{MIN}_\sigma}\right) + 30\left(1 - \frac{M_\mathrm{i} - \mathrm{MIN_M}}{\mathrm{MAX_M} - \mathrm{MIN_M}}\right) + 20\left(1 - \frac{\delta_\mathrm{i} - \mathrm{MIN}_\delta}{\mathrm{MAX}_\delta - \mathrm{MIN}_\delta}\right) \qquad \text{(Eq 2)}$$

where σ, *M*, and δ represent results for bond strength, contamination, and distortion respectively; i is the experimental trial number; MIN and MAX are the minimum and maximum values in each result column; and 50, 30, and 20 are weights applied to the evaluation criteria. The determination of weighting factors is based on the importance of these evaluation values to the acceptance standards of thermally sprayed coupons. While it is somewhat judgmental, the purpose here is to demonstrate the methodology used in this study.

3.5 Bond Strength

The maximum bond strength measured in this study can be correlated with blasting parameters using linear regression:

$$\text{Bond Strength} = 38.7A + 76.9B + 414.2C + 182.6D + 20.6E \qquad \text{(Eq 3)}$$

It can be observed from this equation that the bond strength increases with blasting pressure (*B*), number of passes (*C*), grit size (*A*), and blasting angle (*E*). It needs to be reiterated here that

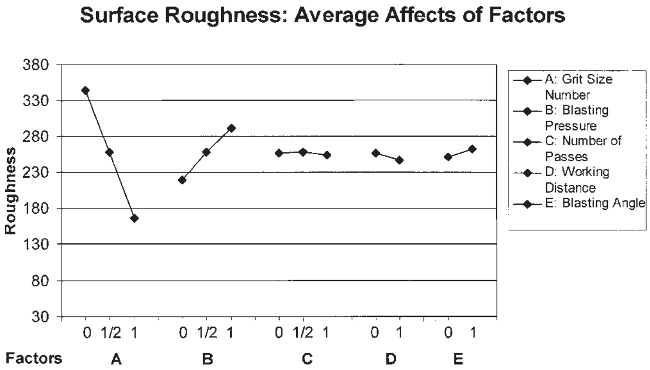

Fig. 3 Average effects of factors on surface roughness

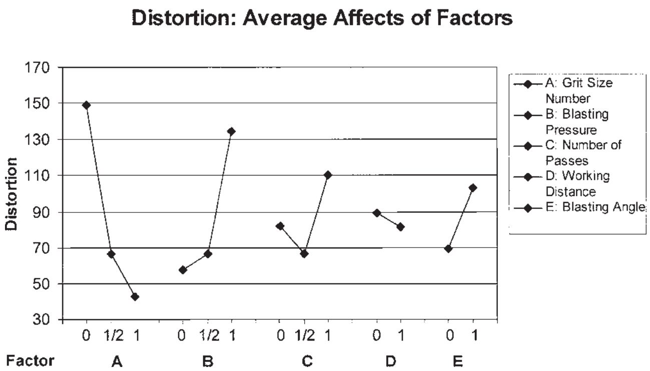

Fig. 4 Average effects of factors on distortion

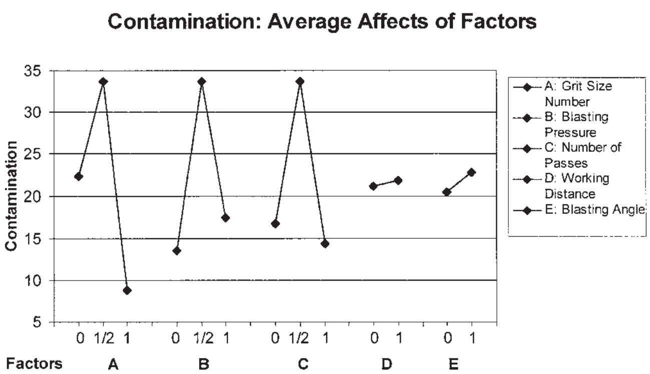

Fig. 5 Average effects of factors on grit contamination

the larger the grit size number, the finer the grit. It suggests that by using finer blasting grit, high bond strengths would be expected.

The probability of each coefficient (p-level) is given in Table 4, with the blasting pressure (B) and number of passes (C) having the most significant effect. The working distances (D) between 4 and 6 in. did not seem to correlate with the bond strength, while the other two variables, grit size (A) and blasting angle (E) showed reasonable probability. R^2 of 95.6% was obtained for the given linear regression equation, indicating that 95.6% of the bond strength value can be calculated using Eq 3.

Table 4 Linear regression weights for bond strength (without intercept, $R^2 = 0.956$)

Variables		p level	Probability, $1 - p$
A	Grit size number	0.057	94%
B	Pressure	<0.01	>99%
C	No. of passes	<0.01	>99%
D	Working distance	0.44	56%
E	Blasting angle	0.075	91%

The average response curves for bond strength are given in Fig. 2. It is apparent by the span of the lines for variables/factors of grit size (A), blasting pressure (B), number of passes (C), and working distance (D) that the bond strength is greatly influenced by these parameters and is somewhat insensitive to the blasting angle (E). For all the curves shown in Fig. 2, no maximum point was observed, suggesting that the variables and variable combination selected did not produce optimal bond strength. There is a difference between average response curves and the linear regression results: according to the average response graph, an increase of working distance produces lower bond strength, but the opposite trend is observed in Eq 3. However, as shown in Table 4, the correlation between bond strength and working distance (D) is poor, and the relationship in Eq 3 is inclusive.

3.6 Surface Roughness

Surface roughness showed a very high level of correlation with all the parameters examined in this study. As shown in Table 5, all the factors exhibit a significant ($1 - p > 99\%$) effect on the surface roughness. Equation 4 gives the linear regression equation for surface roughness in relation to the five independent variables:

$$\text{Surface roughness} = -3.5A + 2.8B + 12.6C + 23.9D + 0.8E \qquad \text{(Eq 4)}$$

Compared with the bond strength, the surface roughness increases in a similar trend with pressure (B), number of passes (C), working distance (D), and blasting angle (E) and has an inverse relationship with the grit size (A). From Eq 3 and 4, it can be observed that the maximum bond strength is not necessarily achieved when the roughness value is at its maximum.

Contrary to the linear regression results, Fig. 3 shows that based on the average response curves, only grit size (A) and blasting pressure (B) have any significant affect on the surface roughness. However, grit size (A), blasting pressure (B), and blasting angle (E) (with little influence) showed the same trend in both the linear regression equation and average response curves. It needs to be noted that all the response curves shown in Fig. 3 were linear in nature, which is also demonstrated in the high correlation probability for Eq 4.

3.7 Distortion Measurement

Distortion occurred as a result of grit blasting, and measurements were used to conduct a linear regression. The following equation shows the correlation of distortion with the factors:

$$\text{Distortion (mil)} = -2.98A + 2.67B + 8.18C - 0.39D + 0.81E \qquad \text{(Eq 5)}$$

Table 5 Linear regression weights for roughness (without intercept, $R^2 = 0.957$)

Variables		*p* level	Probability, $1 - p$
A	Grit size number	<0.01	>99%
B	Pressure	<0.01	>99%
C	No. of passes	<0.01	>99%
D	Working distance	<0.01	>99%
E	Blasting angle	<0.01	>99%

All the variables have shown a strong relationship with the dependent; i.e., greater than 99% of the results can be predicted using the linear regression equation (Table 6). The distortion was observed to increase with the pressure, number of passes and blasting angle, and decrease with grit size number and working distance (i.e., finer grit size and longer working distance reduces the amount of distortion). Similar trends are evident in the average response curves, particularly for variables of grit size (*A*), blasting pressure (*B*), working distance (*D*), and blasting angle (*E*) (Fig. 4) with grit size and blasting pressure having the most influence on the amount of distortion. It was also observed that variable for working distance (*D*) has a minimal impact on the distortion measurement.

3.8 Grit Contamination

In comparison with the other dependent variables, the grit contamination showed a relationship between the variables (Eq 6) with a relatively low confidence level ($R^2 = 0.81$), see Table 7.

$$\text{Grit Contamination} = -0.33A + 0.24B + 0.44C + 2.87D + 0.12E \quad \text{(Eq 6)}$$

The low confidence levels for grit contamination are further illustrated on the average response graph in Fig. 5. While working distance (*D*) and blasting angle (*E*) show little influence, grit size (*A*), blasting pressure (*B*), and number of passes (*C*) have a larger span and all curves did not show a linear relationship.

3.9 Effect of Various Variables on OEC

Results for bond strength, contamination, and distortion were combined into an OEC, as described in Sec. 3.4. The OEC values (provided in Table 3) were then used to create an overall average response graph (Fig. 6). This graph shows that grit size (*A*) again plays a significant role in the overall evaluation, which is followed by blasting pressure (*B*) and number of passes (*C*), with both working distance (*D*) and blasting angle (*E*) exhibiting minimal effects. Again, it is observed that all three variables for grit size (*A*), blasting pressure (*B*), and number of passes (*C*) do not have linear relationships with the overall evaluation values, suggesting strong interaction between the independent variables and possibly higher orders of relationship. Figure 5 also gives a prediction for the best combination of factor level settings (experiment #27); i.e., grit size = 54, blasting pressure = 20 psi, number of passes = 8, working distance = 4 in., and blasting angle = 45°. This combination may also become evident after the individual response graphs are studied. Recall that since the experiment used a full factorial method, this combination was

Table 6 Linear regression weights for distortion (without intercept, $R^2 = 0.906$)

Variables		*p* level	Probability, $1 - p$
A	Grit size number	<0.01	>99%
B	Pressure	<0.01	>99%
C	No. of passes	<0.01	>99%
D	Working distance	<0.01	>99%
E	Blasting angle	<0.01	>99%

Table 7 Linear regression weights for grit contamination (without intercept, $R^2 = 0.81$)

Variables		*p* level	Probability, $1 - p$
A	Grit size number	<0.01	>99%
B	Pressure	0.06	94%
C	No. of passes	0.62	38%
D	Working distance	0.03	97%
E	Blasting angle	0.094	91%

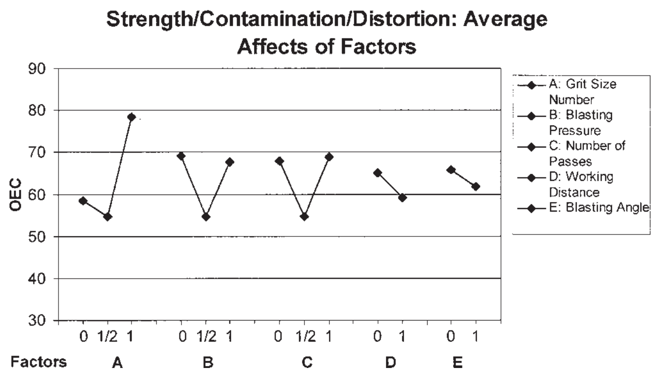

Fig. 6 Average effects of factors on OEC

tested. Trial No. 27 had the highest OEC value out of all the trials at 96.32, as shown in Table 3.

4. Discussion

It is known that adhesion of thermally sprayed coatings depends critically on the condition of the surface before spraying, and the grit-blasting process provides the essential roughened surface. However, grit blasting, in most practices, has been developed in an empirical and qualitative manner, which is often inadequate in a modern manufacturing environment striving for predictability and zero defects. A good understanding of how the process parameters contribute to the coating properties, and a feasible method for process control can allow industry to achieve manufacturing excellence. This study was initiated to investigate the relationship between the process variables/factors and evaluated properties to meet industrial standards. An additional objective was to develop statistical methods so similar exercises could be conducted on different substrate materials or blasting equipment. In the following subsections, a summary of the results is given, and each property measured in this study will be discussed and compared with the available results from other investigators.

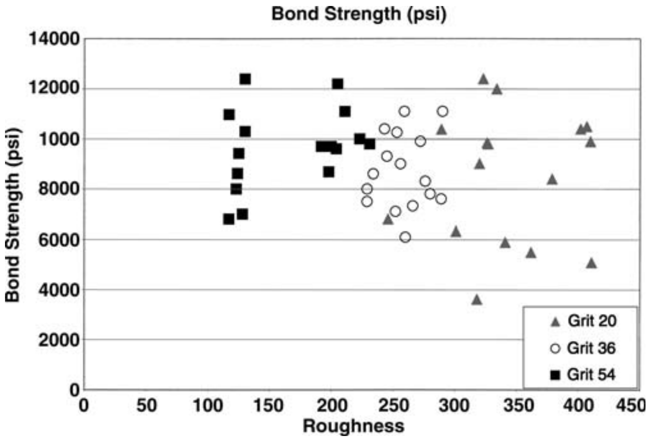

Fig. 7 Bond strength versus roughness

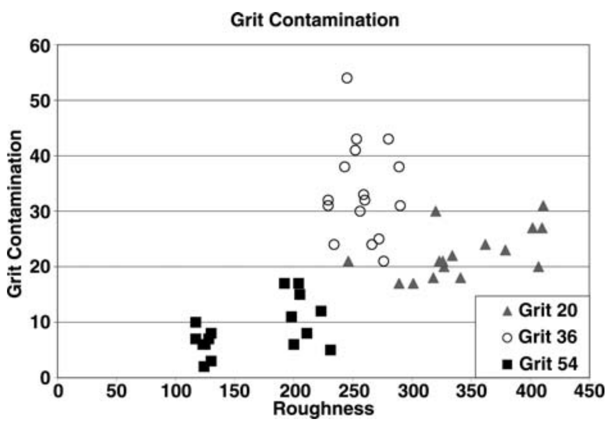

Fig. 8 Grit contamination versus roughness

The above results detail how the various process parameters affect the properties of the blasted surfaces. The linear regression results are summarized in Table 8, with each column showing the coefficients of the regression equations. Also seen in the shaded areas are significant variables summarized from average response curves. From the table, it can be determined that grit size (*A*) affects four dependent properties strongly but in different ways. It has positive influence on the bond strength and negative influence on roughness, distortion, and contamination within the variable range examined here. If the grit size (*A*) were the only variable studied, a statement could be made that bond strength and roughness have an inverse relationship, i.e., the rougher the surface, the lower the bond strength. On the other hand, if grit size (*A*) was not included in this study, the bond strength and surface roughness would show positive correlation with the other four variables, *B*, *C*, *D*, and *E*. Blasting pressure (*B*), number of blasting passes (*C*), and blasting angle (*E*) have similar positive effects on all the dependent properties examined here. Pressure (*B*) has a significant influence on all the properties as shown by the shaded area. However, the last two variables, working distance (*D*) and blasting angle (*E*), showed very insignificant impact on the dependent variables studied. This summary table indicates that the two most important parameters to look at when developing grit blasting process are grit size (*A*) and blasting pressure (*B*).

4.1 Roughness and Bond Strength

Roughening of surfaces using the grit-blasting process as a method to improve adhesion is a controversial topic in the literature, as described in Sec. I. In this study, the surface roughness is observed, based on both linear regression and average response curves, to increase with the decreasing of grit size number (increasing of the actual grit size), which agrees well with the general published observations (Ref 4, 8). Additionally, blasting angle and distance had a positive impact on the roughness based on the linear regression calculations, which was different from the conclusions made in the other study where blasting angle and distance were not observed to affect the surface roughness (Ref 8). However, the average response results (Fig. 3) seem to agree more closely with the published work as both blasting angle and distance had very little influence, from the span of the response curve, on the surface roughness. Conversely, the number of blasting passes (similar to blasting time) showed a positive influence, from the linear regression equation, on the surface roughness and agreed well with the previous observation (Ref 8). The blasting angle at 90° produced rougher surface than that at 45°. As a mid point, 75° for example, was not evaluated in this study, it is difficult to compare this finding to the findings in Ref 9.

To examine whether there is a relationship between the bond strength and roughness, the bond strength was plotted against the roughness, as shown in Fig. 7. A random distribution can be observed in general, which indicates that there is no true relationship between these two properties as was observed in many publications. Previous publications (Ref 7-9) have also concluded that the surface roughness is not a true representation of surface morphology, and as such it cannot be used to predict the bond strength. However, when the grit size is differentiated on the figure, it is seen that when finer grit (#54 or 36) was used, the surface roughness is normally lower, and more importantly the bond strength seems to be higher irrespective of other blasting variables used. Additionally, the range of the bond strength distribution is also narrower when finer grit size was used. On the other hand, when coarser grit (#20) was used, the bond strength varies widely from 3600 to 12,400 psi. It is important to note from this observation that a grit-blasting process can be controlled under tighter tolerance when using finer grit. Because the grit-blasting process studied here had process parameters selected to be within the ranges for practical use, future research should expand the variable range to determine whether there is a true relationship between bond strength and surface roughness.

The bond strength in this study was observed to increase with an increase of most of the process parameters, grit size number (*A*), pressure (*B*), and number of passes (*C*) (equivalent to blasting time) as predicated from linear regression Eq 3. On the other hand, a decrease in working distance (*D*) and blasting angle (*E*) contribute to higher bond strength based on the average response calculations (Fig. 2). This indication of a decrease in distance and angle improving bond strength contradicts the linear regression results. It should, however, be noted that these two parameters gave lower statistical significance values of 56% and 91%, respectively. The results do not agree with the study conducted

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Table 8 Summary of the statistical analysis results

Measured properties	Grit size, *A*	Pressure, *B*	Number of passes, *C*	Working distance, *D*	Blasting angle, *E*
Bond strength	**38.7**(a)	**76.9**	**414.2**	**182.66**(a)	20.66(a)
Roughness	**−3.45**	**2.76**	12.62	23.92	0.8
Distortion	**−2.98**	**2.67**	**8.18**	−0.39	**0.81**
Grit contamination	**−0.33**	**0.24**(a)	**0.44**(a)	2.87(a)	0.12(a)

Bold text represents significant influence judged from average response curve. (a) Probability <99%

by Harris et al. (Ref 4) where no difference in strength between fine and coarse grit was found.

From the results described in Sec. 3.5 and Table 8, it is apparent that variables for grit size (*A*), pressure (*B*), number of passes (*C*), and working distance (*D*) played a significant role in determining the bond strength. Among these four variables, grit size (*A*), pressure (*B*), and number of passes (*C*) can be used to predict the bond strength using the linear regression Eq 3 with reasonable confidence. The influence of a variable for blasting angle (*E*) to the bond strength is minimal and the relationship between working distance (*D*) and the bond strength cannot be accurately predicated using multiple linear regressions. It is felt that the combination of variables (such *AD*, *BD*, *CD*…) and higher orders of working distance (*D*) (such as D^2) need to be incorporated into the regression equation in order correlate the bond strength and working distance (*D*).

4.2 Distortion

The linear regression (Table 6) and average response (Fig. 4) analyses for distortion are in closer agreement than any of the other evaluation criteria. Though the average response curves indicate the influence of grit size and blasting pressure as the most significant on distortion, linear regression gives more emphasis on number of passes. Distortion can be minimized by using smaller grit and a lower blasting pressure, both of these level settings being predicted for the overall optimized process.

Distortion and roughness showed a very close trend when analyzed using multiple linear regression method, except for working distance (*D*). A high probability level ($1-p>99\%$) was observed for all variables *A*, *B*, *C*, *D*, and *E*. However, when considering average response curves in Fig. 3 and 4, it is found that the number of blasting passes (*C*) did not have the same impact on surface roughness and distortion. Increasing the number of blasting passes (*C*) or duration could increase the distortion while not widely contributing to the surface roughness. This implies that the blasting passes or duration needs to be controlled becuase a further increase in the number of blasting passes will result only in an increase in component distortion.

4.3 Grit Contamination

A typical feature of grit-blasted surfaces is the presence of embedded grit. In this study, the grit contamination was evaluated by counting the total number of grit in a constant area; however, the grit size was not taken into consideration, which would affect the amount of total area of coverage and also the adhesion. An alternative method was attempted using a chemical process: dissolving Al_2O_3 into acid and measuring the Al^{+++} concentration. However, the methods could not provide repeatability at this time.

It was noted in other studies that depending on the blasting angle, up to 10% of a steel surface could be covered by embedded grit, which causes a serious adhesion problem. The higher the blasting angle, the higher the contamination (Ref 13, 14). This was observed in Tables 7 and 8; the increased blasting angle resulted in elevated grit contamination, which is obtained from both the linear regression equation and average response curves. It was reported that smaller particle size (higher grit size number) apparently leaves a greater percentage of contaminant residues on the surface (Ref 4). To further illustrate the grit size effect on surface contamination and the relationship between surface roughness and contamination, Fig. 8 was plotted to include grit size, surface roughness, and contamination. It is observed from this figure, that when using finer grit such as #54, the surface contamination determined using particle counting was low and exhibited two clusters, which were separated by the difference in blasting pressure. Low blasting pressure gives lower roughness values, and the surface contamination was low and not affected to a large extent. On the other hand, when the intermediate grit was used, the surface contamination appeared to be the highest. This could be the results of both particle size (to be large enough to be observed during grit count under 40× magnifications) and number of particles involved during blasting process (more particle counts for finer grit size under constant mass flow rate). There is no relationship observed between the surface roughness and contamination with grit #36. When large grit was used, an increasing trend was observed from Fig. 8 between surface contamination and roughness. The overall trend, irrespective of grit size and other process variables, seems to show a positive relationship between surface roughness and contamination. This increased surface contamination achieved concurrently with increased surface roughness could possibly counterbalance the roughness effects on the bond strength; however, this requires further investigation.

The amount of grit residue was also increased by blasting pressure in general, as shown in Fig. 5, which again agrees with the published research (Ref 8). Increase in grit contamination has been observed to cause a reduction in the adhesion strength of plasma coatings (Ref 1); however, this is not conclusive from this study since a somewhat random distribution between surface contamination bond strength was found.

From Table 7 and Eq 6, it can be observed that grit contamination, evaluated using total number of embedded particles in a controlled area, showed positive correlation with blasting pressure (*B*), working distance (*D*), and blasting angle (*E*) and a negative relationship with grit size (*A*). It should also be noted that the statistical significance was lower for all variables, except for grit size, which is further illustrated by the lack of linear trends in the average response curves (Fig. 5).

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5. Conclusions

For an evaluation of thermal spray coatings in an industrial environment, there are two main interests in relation to the grit blasting process, namely bond strength and interface grit contamination. Maximizing the bond strength and reducing the grit contamination, while at the same time reducing the component distortion, would improve the productivity significantly by reducing the reject rate. From this study, it can be concluded that to achieve these goals, a larger grit size number (finer grit) should be used, for the specific substrate material (Hastelloy X). Individually, the parameters can be adjusted according to Eq 3 and 6. To improve the bond strength, it is necessary toincrease the blasting pressure (*B*), increase the number of passes (*C*), and increase grit size number (*A*). To minimize contamination, the following approaches can be used: reduce pressure (*B*) within the range examined here, increase grit size number (*A*), and reduce the number of blasting passes (*B*). There is obviously a tradeoff with regard to the pressure (*B*) and passes (*C*). If low bond strength is a problem, pressure and passes need to be increased; alternatively, if contamination is a problem, reducing pressure and angle is recommended.

The correlation of each variable with the dependents can be summarized based on the linear regression method and average response curves as follows:

- The linear regression equation can predict 96% of the bond strength values using the process parameters. Only working distance (*D*) within the range selected did not seem to correlate well with the bond strength and blasting angle showed insignificant contribution to the bond strength.
- Surface roughness can be predicted successfully with the given equation $R^2 = 0.97$, and a linear relationship is also observed from the average response curve. Both grit size (*A*) and blasting pressure (*B*) show a high level of influence to the surface roughness and all the variables are related to the surface roughness with high probabilities.
- Distortion can be related to all the process variables with good confidence (90%); working distance (*D*) exerted the least impact on the distortion. The four variables, grit size (*A*), blasting pressure (*B*), working distance (*D*), and blasting angle (*E*), showed a linear relationship with the distortion.
- About 80% of the surface contamination measurements showed a relatively poor relationship with blasting pressure (*B*), number of passes (*C*), working distance (*D*), and blasting angle (*E*) as illustrated by low probabilities and a low R^2 value. However, the average response curves indicated that grit size (*A*), blasting pressure (*B*), and number of passes (*C*) could have the most significant effects on the grit contamination.

6. Industry Recommendations

Linear regression is a powerful statistical tool that can provide manufacturers with important information regarding their processes. With established procedures, linear regression can be adopted for process control and optimization provided the proper software and expertise is available. However, the linear regression method does not take into consideration the interaction between variables, which could result in poor correlation between independent variables and dependent variables. Conversely, applying the average response method can be easily designed to carry out all necessary calculations with only raw measured data as the input. The output, however, is visual and simple to disseminate with graphs and a definite set of predicted parameter settings. Another advantage of the average response method is the ability to use fractional factorial experiment designs, greatly reducing the number of required experimental trials. Used in combination with the Taguchi Approach for design of experiments, this is a powerful industry tool that is very straightforward and becoming increasingly beneficial (Ref 15, 16). The Taguchi method describes further tools that can be used to optimize process and product quality, such as analysis of variance (ANOVA) and signal-to-noise (S/N) ratio analysis (Ref 11, 12). Based on the results and analysis presented in this paper, the average response method would be a useful everyday tool for the industry in terms of process control and improvement. For advanced and detailed analyses, perhaps for a newly introduced process or piece of equipment, linear regression would be an invaluable tool for establishing baseline process parameters and relationships between these factors and the measured evaluation criteria.

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