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SURFACE PREPARATION OF STEEL SUBSTRATES USING GRIT-BLASTING

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Abstract

The primary purpose of 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 statistically designed experiments that were accomplished to investigate the effect of abrasives on roughness for A36/1020 steel. The experiments were conducted using a Box statistical design of experiment (SDE) approach. Three grit blasting parameters and their effect on the resultant substrate roughness were investigated. These include blast media, blast pressure, and working distance. The substrates were characterized for roughness using surface profilometry. These attributes were correlated with the changes in operating parameters. Twin-Wire Electric Arc (TWEA) coatings of aluminum and zinc/aluminum were deposited on the grit-blasted substrates. These coatings were then tested for bond strength. Bond strength studies were conducted utilizing a portable adhesion tester following ASTM standard D4541.

1.0 Introduction

Preparation of substrates for thermal spray coatings involves the spraying of abrasive particles against the substrate to remove contaminants and to condition the surfaces for subsequent spraying operations. Thermal spray processes are currently being used in over 50 industries for a variety of applications. Maximum bond strength is the most important coating attribute relative to thermal spray coatings, since the coatings rely primarily upon mechanical bonding. Thus, it is crucial that the substrate be properly prepared to ensure maximum coating bond strength. Surface cleanliness and roughness are the most critical factors. 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/contamination to minimize coating failures.

Three practical grit size ranges are: coarse 2.0 to 0.6 mm (–10 to +30 mesh), medium 1.4 to 0.425 mm (-14 to +40 mesh), and fine 0.60 to 0.18 mm (-30 to + 80 mesh). The selection of grit size, type, and hardness provides the primary results of surface preparation. Other factors include air pressure, working nozzle distance, and angle. Typically, coarse grit is used for coatings exceeding 10 mils for best adhesion, medium grit is used for smoother finishes of coatings less than 10 mils with fair adhesion, and fine grit is used for the smoothest finishes on coatings less than 10 mils to be used in the as-sprayed condition. Thus, the selection of the grit size is partially determined by the required coating thickness, and considered on an individual basis for each application.

Alumina, silica sand, steel, 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 is commonly used on steel. Consideration should be given to the substrate materials in the selection of grit types. Traces of residual grit may adversely affect some coatings. Alumina, sand, and especially silicon carbide may embed in softer metals such as aluminum, copper, and their alloys. For these metals, lower working air pressures are typically used to minimize embedding.

Grit blasting air pressure varies from 210 to 827 kPa (30 to 120 psia) with a wide range of working distances of 50 to 914 mm (2 to 36 in.) depending on the application. Nozzle sizes are generally 3 to 16 mm (0.125 to 0.625 in.) in diameter. The blasting angle to the substrate can vary from 60 to 90 degrees.

Statistical design of experiments (i.e. SDE) has been rigorously developed for over 80 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 SDE methodology for the grit blast process. Use of this methodology results in optimized surface roughness, and resulting coating bond strength, by obtaining a scientific understanding of the physical mechanisms involved in the preparation of substrates for thermal spraying. Tasks involved in this study included (1) measuring the effect of various abrasives on roughness for A36/1020 steel used in fabricating steel structures (e.g. bridges), (2) comparing the response of steel abrasives versus conventional abrasives used for grit blasting, and (3) testing the bond strength of TWEA sprayed coatings on the substrates grit blasted with the aforementioned materials.

Zinc and aluminum coatings find widespread applications in the automotive, transportation, aerospace, and aircraft industries. The material systems are commonly used for anti-corrosion applications for infrastructure. Smooth coatings with low porosity, low oxide content, and high bond strength are desired in most applications.

2.0 Experimental Procedure

A modified Econoline, RA 36-1 grit blasting device [3], illustrated in Figure 1, was utilized for this study. The Econoline cabinet is rectangular in shape and is a self-contained, recycling, sealed glove box design. It is capable of blasting small pieces, up to 12 cm (30.5 inches) in length. The abrasive hopper that is located below the worktable holds between 11.4 to 22.7 kg (25 to 50 lbs.) of blasting material. The spray gun consists of a 708 lpm (1500 scfh) carbide nozzle and a 708 lpm (1500 scfh) 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 70 to 827 kPa (10 to 120 psia). An external dust collector sweeps and filters the air in the cabinet to improve visibility during blasting operations.

Box standard design of experiments [4] were used to optimize the process parameters for the grit blast equipment. This statistical analysis was accomplished with the use of the Design-Expert software [5]. 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 (D = 5.1 to 10.2 cm, 2 to 4 inches), blast pressure (P = 560 to 827 kPa, 80 to 120 psia), and blast media. All the grit blast studies utilized factorial designs, as illustrated in Table 1 for the steel grit studies. Each variable has fixed ranges selected to determine the parameter space for surface preparation optimization. The substrates used for the studies were low carbon

Figure 1. Econoline, RA 36-1 Grit Blaster

steel (A36/1020). All manipulation of the devices was done manually.

Two major grit blast studies were conducted. Experiments E01 through E52 used Ervin Amasteel media HG16 (16 mesh), HG18 (18 mesh), HG25 (25 mesh), and HG40 (40 mesh). These experiments were conducted to determine the characteristics of steel grit for grit blasting. A 3-level response surface factorial experiment shown in Table 1 was utilized. A quadratic model yielded the best fit to the data. Experiments C01 through C41 were then conducted for comparison to the steel studies. Conventional grit blast materials (i.e. copper slag (30 mesh), coal slag (30 mesh), and chilled iron (40 mesh) were used for these studies. Again, a 3-level response surface factorial experiment was utilized. A quadratic model again yielded the best fit to the data. The roughened substrates produced by grit blasting with the metal grit appear to be relatively free from embedded grit or surface scale particles, while the substrates blasted with the slag grits appeared to have some embedded grit.

Roughness Characterization and SDE Results

Surfaces of the substrates grit blasted with the various materials were examined for roughness. Surface roughness was determined using a Surftest 301 roughness tester [6]. The Surftest 301 unit provides digital readout of the measuring conditions and results for nine types of roughness parameters including Ra (arithmetic mean deviation of the profile), Rq (RMS deviation of the profile), R3z (mean

Table 1. Full-Factorial Design of Experiment

Exp. #	Dist. (D) lev/cm/inch	Press. (P) lev/kPa/psia	Grit type level/type
1	1 / 0.79 / 2	1 / 555.2 / 80	1 / HG16
2	2 / 1.18 / 3	1 / 555.2 / 80	1 / HG16
3	3 / 1.57 / 4	1 / 555.2 / 80	1 / HG16
4	1 / 0.79 / 2	2 / 694 / 100	1 / HG16
5	2 / 1.18 / 3	2 / 694 / 100	1 / HG16
6	3 / 1.57 / 4	2 / 694 / 100	1 / HG16
7	1 / 0.79 / 2	3 / 832.8 / 120	1 / HG16
8	2 / 1.18 / 3	3 / 832.8 / 120	1 / HG16
9	3 / 1.57 / 4	3 / 832.8 / 120	1 / HG16
10	2 / 1.18 / 3	2 / 694 / 100	1 / HG16
11	2 / 1.18 / 3	2 / 694 / 100	1 / HG16
12	2 / 1.18 / 3	2 / 694 / 100	1 / HG16
13	2 / 1.18 / 3	2 / 694 / 100	1 / HG16
14	1 / 0.79 / 2	1 / 555.2 / 80	2 / HG18
15	1 / 1.18 / 3	1 / 555.2 / 80	2 / HG18
.	.	.	.
.	.	.	.
52	.	.	4 / HG40

peak-to-valley height), Rt (maximum peak to valley height, Ry (maximum peak to valley height Zi), Rz (average peak to valley height), Rp (maximum profile peak height), tp (bearing length ratio), and Pc (peak count). Rz was chosen to be used for the primary roughness measurement since it most closely matches ANSI standard B46.1 (i.e. the average deviation from the mean line of elevation through the surface asperities).

Figure 2 illustrates the results of the metal grit study. Rz, the peak-to-valley grit blasted profile, is illustrated as function of working distance and a constant pressure of 694 kPa (100 psia) for the four steel grits. As illustrated, the HG16 grit obtains the maximum Rz profiles, followed by HG18, HG24, and HG40. Maximum Rz average roughness for the metal grit ranged from 2.93 to 3.98 mils for the HG16, 3.04 to 3.80 mils for the HG18, 2.44 to 3.31 mils for the HG24, and 1.85 to 2.49 mils for the HG40.

The optimum metal grit (i.e. HG16) was then compared to the conventional abrasives. Figure 3 illustrates the results of this study. As shown, the metal grit HG16 attains a larger Rz profile than the copper slag, coal slag, and chilled iron. The response surface plots for roughness Rz are presented as a function of working distance and working pressure for the four abrasives. As illustrated, the HG16 grit (3a) obtains the maximum Rz roughness ranging from 2.93 to 3.98 mils. The Rz roughness for the conventional abrasives ranged from 2.46 to 3.09 mils for copper slag (3b), 1.95 to 2.88 mils for coal slag (3c), and 1.81 to 2.27 mils for chilled iron (3d). The trends for increasing roughness for coal slag and chilled iron grit follow the trends exhibited with the HG16 grit: i.e. Rz increases as the working distance increases, with the roughness reaching a maximum at intermediate pressure (i.e. ~694 kPa, 100 psia).

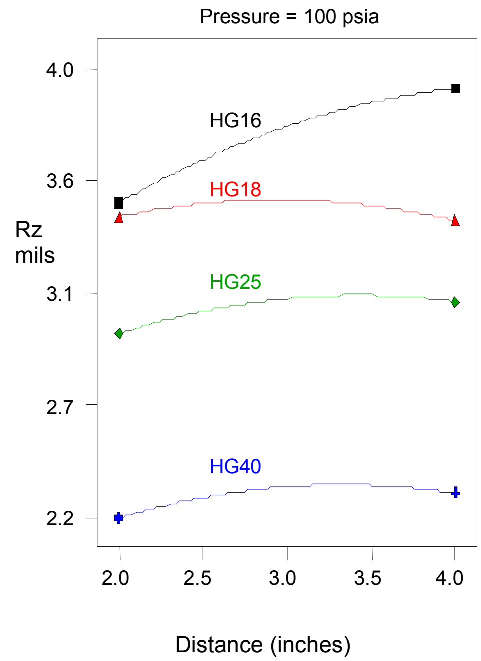

Figure 2. Steel Grit Roughness

Once the effects analysis of the process parameters has been determined, analysis is conducted to find the levels of the parameters that lead to a particular response (e.g. maximum). Graphical procedures based upon normal probability plots were used for all of the SDE cases in this study to choose an appropriate regression model for each response. Once this analysis was completed, the ANOVA (analysis of variance) calculations were conducted for each response. Once the statistical values of the F value (i.e. the comparison of the treatment variance with the error variance), the probability value (i.e. the probability that the model terms are null), and the coefficient of variation (CV) yielded robust values, equations were generated which yielded the response surface plots for Figures 2 and 3. The final roughness equations in terms of the actual processing factors for each grit are illustrated in equations 1 through 7.

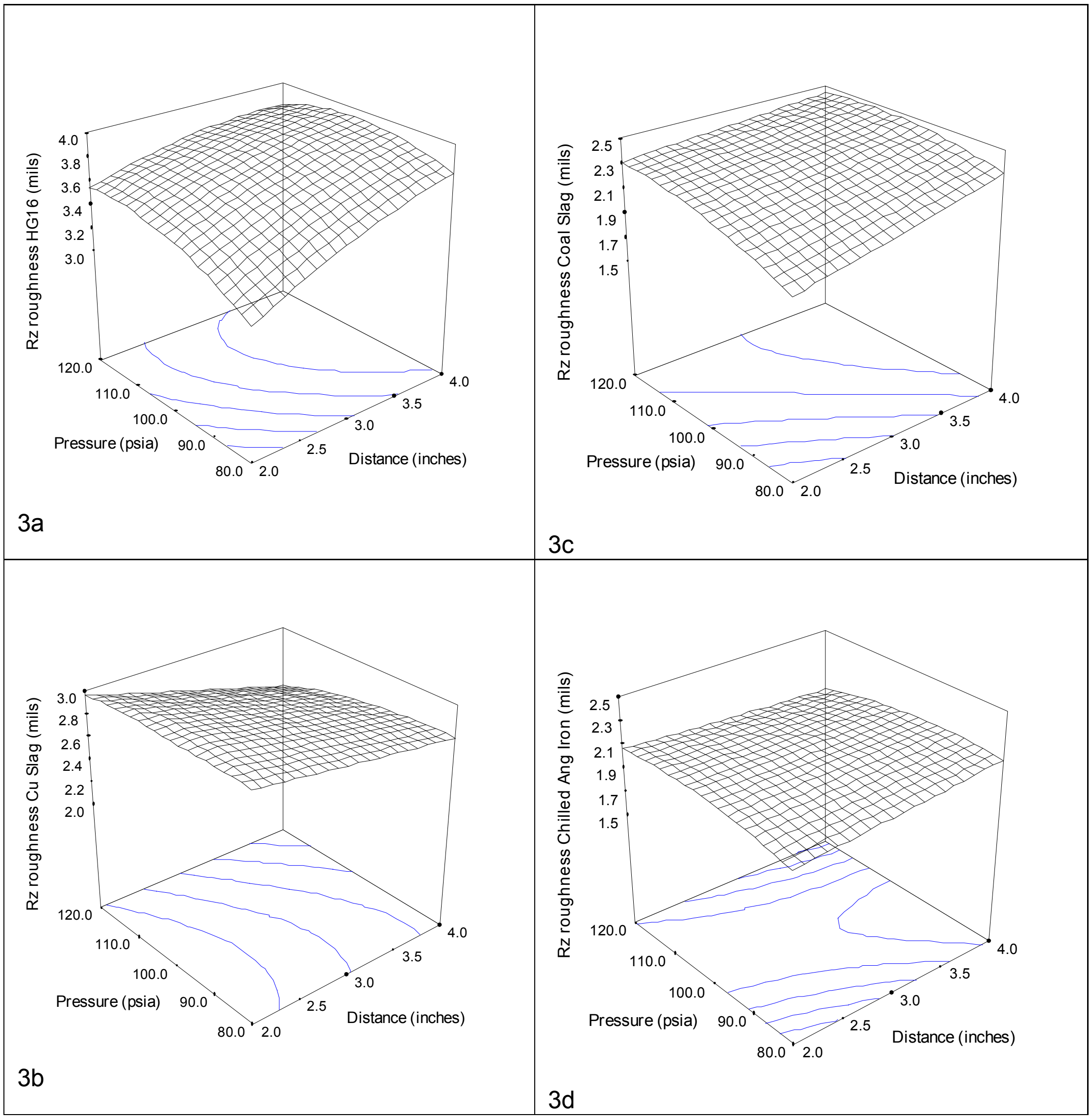

Figure 3. Roughness Comparison of HG16, Copper Slag, Coal Slag, and Chilled Iron Grit

$$Rz\ HG16 = -3.01 + 1.14*D + 0.09*P - 0.074*D^2 - 3.45E\text{-}4*P^2 - 4.71E\text{-}3*D*P \quad \text{Eq. 1}$$

$$Rz\ HG18 = -2.9 + 0.9*D + 0.09*P - 0.074*D^2 - 3.45E\text{-}4*P^2 - 4.7*D*P \quad \text{Eq. 2}$$

$$Rz\ HG25 = -3.28 + 0.98*D + 0.09*P - 0.074*D^2 - 3.45*P^2 - 4.71E\text{-}3*D*P \quad \text{Eq. 3}$$

$$Rz\ HG40 = -3.77 + 0.96*D + 0.088*P - 0.074*D^2 - 3.45E\text{-}4*P^2 - 4.71E\text{-}3*D*P \quad \text{Eq. 4}$$

$$Rz\ Cu\ slag = +1.1 + 0.087*D + 0.042*P + 4.34E\text{-}3*D^2 - 1.81E\text{-}4*P^2 - 3.04E\text{-}3*D*P \quad \text{Eq. 5}$$

$$Rz\ Coal\ slag = -1.34 + 0.4*D + 0.05*P + 4.34E\text{-}3*D^2 - 1.81E\text{-}4*P^2 - 3.04E\text{-}3*D*P \quad \text{Eq. 6}$$

$$Rz\ C.\ A.\ Iron = -0.6 + 0.29*D + 0.045*P + 4.38E\text{-}3*D^2 - 1.81E\text{-}4*P^2 - 3.04E\text{-}3*D*P \quad \text{Eq. 7}$$

Analysis was then conducted to determine the optimum parameters for the maximum Rz roughness attainable for each grit. This methodology involved numerical optimization to search for a combination of factor levels that simultaneously satisfies the requirements placed on each of the responses. The maximum attainable roughness for each blasting material is illustrated in Table 2 with the corresponding process parameters. The HG16 steel grit attained the highest predicted roughness of all the grits.

Coating Characterization and SDE Results

The twin-wire electric arc spray process was chosen for this application because it can produce

Table 2. Maximum Predicted Roughnesses

Grit Type	Distance (cm/in.)	Pressure (kPa/psia)	Rz (mils)
HG16	1.57 / 4	694 / 100	3.92
HG18	0.79 / 2	832 / 120	3.55
HG24	1.57 / 4	694 / 100	3.09
HG40	1.18 / 3	694 / 100	2.36
Cu Slag	0.79 / 2	694 / 100	3.04
Coal Slag	1.57 / 4	694 / 100	2.45
Chilled Iron	1.57 / 4	694 / 100	2.11

high purity, low porosity coatings with high bond and interparticle strength. A Tafa, Inc. Model 9000 TWEA spray system and commercially available wire (i.e. Tafa 01T aluminum, Tafa 02A 85Zn/15Al) were used. Table 3 illustrates the SDE for the aluminum coatings using the HG16 steel grit. A response surface central composite statistical design of experiment was conducted using a quadratic design model. Each variable has two levels selected to band around the nominal settings (i.e. exp. 1 through 8). Centerpoint experiments (i.e. 13 through 17) were also included to independently evaluate the process variation.

The process parameters utilized in the experiments included orifice diameter (green nozzle cap = 0.767 cm, 0.302 in.) system pressure (i.e. P), current (i.e. A = amperes), and spray distance (i.e. D). Air was used as the primary and shroud gas (i.e. 208.2 kPa, 30 psia). Wire injection was internal to the gun and directed parallel to the flow. Wire feedrate varies proportionally with the system current. The wire feedrates were 2.32 kg/hr (5.1 lb/hr) at 100 A, 4.05 kg/hr, 8.9 lb/hr at 200 A, and 6.68 kg/hr (14.7 lb/hr) at 300 A for the aluminum experiments; and, 7.86 kg/hr (17.3 lb/hr) at 100 A, 16.6 kg/hr (36.5 lb/hr) at 200 A, and 25.36 kg/hr (55.8 lb/hr) at 300 A for the zinc/aluminum experiments. An x-y servo-manipulator ensured the standoff distance and repeatability in the experiments. The traverse x-motion rate was 40.64 cm/in. (16 inches/sec). A y-step of 0.3175 cm (0.125 inches) was used. The wire was thermal sprayed onto A36/1020 low carbon steel coupons (10.16x15.24x0.3175 cm, 4x6x0.125 inches), which were cooled by air jets on the backside. The deposition side of each coupon was grit blasted with HG16 steel grit at a 7.62 cm (3 inch) working distance and 694 kPa (100 psia) obtaining Rz profiles of ~3.9 mils.

Bond strength measurements were conducted using a PATTI3 [7] (Pneumatic Adhesion Tensile Testing Instrument) portable adhesion tester. This instrument follows the test procedure described by ASTM standard D4541. The PATTI3 uses compressed inert gas to apply a continuous tensile load to an aluminum pull stub, which is bonded to the test surface with an adhesive. Once the pull stub has been bonded and the adhesive has cured, a

Table 3. Aluminum/HG16 Experiments

E. #	Dist. cm/in.	Curr. amps	Press. kPa/psia	Bond Stren. kPa/psia
1	7.62 / 3	100	277.6 / 40	12166 / 1753
2	17.8 / 7	100	277.6 / 40	14428 / 2079
3	7.62 / 3	300	277.6 / 40	15282 / 2202
4	17.8 / 7	300	277.6 / 40	15844 / 2283
5	7.62 / 3	100	555.2 / 80	12728 / 1834
6	17.8 / 7	100	555.2 / 80	12728 / 1834
7	7.62 / 3	300	555.2 / 80	15560 / 2242
8	17.8 / 7	300	555.2 / 80	15282 / 2202
9	5.08 / 2	200	416.4 / 60	13859 / 1997
10	20.3 / 8	200	416.4 / 60	16698 / 2406
11	12.7 / 5	100	416.4 / 60	12728 / 1834
12	12.7 / 5	325	416.4 / 60	16698 / 2406
13	12.7 / 5	200	208.2 / 30	15844 / 2283
14	12.7 / 5	200	624.6 / 90	15282 / 2202
15	12.7 / 5	200	416.4 / 60	16413 / 2365
16	12.7 / 5	200	416.4 / 60	16698 / 2406
17	12.7 / 5	200	416.4 / 60	14997 / 2161

continuous load is applied perpendicular to the pull stub until failure occurs. This methodology is reported to generate quantitative tensile strength data with a 2% or better accuracy. The bond strength ranged from 12166 kPa (1753 psia) to 16698 kPa (2406 psia) for the aluminum coatings using the HG16 grit blasted surfaces.

As with the statistical analysis in the roughness study, effects and ANOVA analyses were conducted for bond strength. The I percent (I%) calculation indicates the influence of a factor or parameter on the measured response, with a larger number indicating more influence. The ANOVA calculations guide further experimentation by indicating which parameters are the most influential on coating attributes. High bond strength was most influenced in order by current, spray distance, and pressure. Higher current results in higher bond strength for the coatings as dictated by an I% of 66.4%, while higher spray distance had a I% of 25.2%, and lower pressure an I% of 8.4%. Figure 4 illustrates the cube plot for bond strength, which illustrates the values for the combinations of the upper and lower levels of the three selected processing variables for the aluminum study.

The regression equation for bond strength for the aluminum coatings using the HG16 grit is:

$$\text{Al Bond Strength (HG16)} = +507.2 +167.3*D +8.6*A + 8.6*P -12.8*D^2 -0.0163*A^2 -0.0825*P^2 \quad \text{Eq. 8}$$

A comparison of the effect on bond strength as a function of the type of grit used in this study was then conducted. TWEA zinc-aluminum coatings were deposited on substrates prepared using the best grit

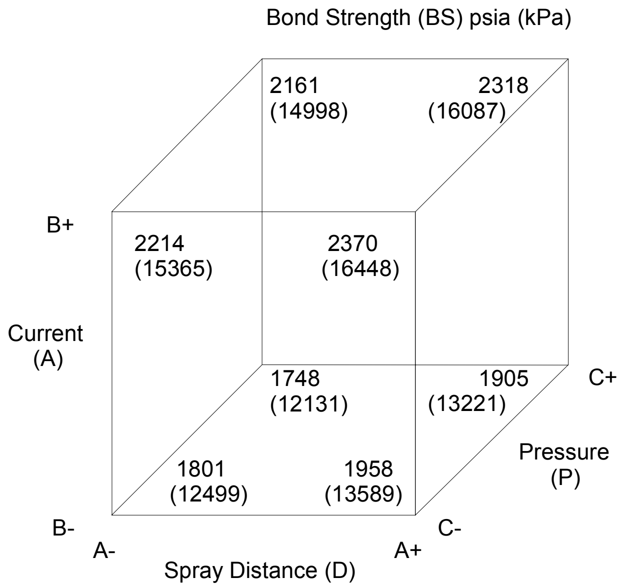

Figure 4. Aluminum Bond Strength for HG16

blast parameters for all seven of the grit materials shown in Table 2. Substrate roughnesses obtained for each grit were consistent with the data illustrated in Figures 2 and 3. Three bond strength tests were conducted for each grit. Table 4 illustrates the results of this classical study.

Table 4. ZnAl Bond Strength for Grit Media

Sample:	Bond Strength kPa (psia)
HG16	7634(1100), 8342(1202), 7819(1141)
HG18	8342(1202), 7819(1141), 8057(1161)
HG25	7634(1100), 7634(1100), 8203(1182)
HG40	9050(1304), 8203(1182), 8481(1222)
Cu Slag	6364(917), 7350(1059), 6787(978)
CoalSlag	6926(998), 6926(998), 7350(1059)
C A Iron	3387(488), 3387(488), 4095(590)

Summary and Conclusions

An experimental study of the grit blast process has been presented. Major parameters investigated included blast media, blast pressure, and working distance. Box-type statistically designed experiments were conducted in order to investigate the effect of abrasives on roughness for A36/1020 steel. The substrates were characterized for surface roughness using surface profiliometry. These attributes were correlated with the changes in operating parameters. TWEA coatings were then deposited on the grit-blasted substrates. These coatings were then tested for bond strength utilizing a portable adhesion tester following the test procedure described by ASTM standard D4541.

The steel grits utilized in this study produced a higher substrate roughness than conventional grit materials (i.e. copper slag, coal slag, chilled iron). The HG16 steel grit obtained the maximum Rz roughness, followed by HG18 steel, HG24 steel, HG40 steel, copper slag, coal slag, and chilled iron. Trend analysis indicated the roughness increased at intermediate pressure (i.e.100 psia), and as working distance increased.

Bond strength measurements were conducted using a PATTI3 portable adhesion tester. The bond strength ranged from 12166 kPa (1753 psia) to 16698 kPa (2406 psia) for the aluminum coatings using the HG16 grit blasted surfaces. Effects analysis conducted for the steel grit bond strength studies indicated high bond strength was most influenced in order by higher current, longer spray distance, and intermediate pressure. TWEA zinc-aluminum coatings were deposited on substrates prepared using the best grit blast parameters for all seven of the grit materials. These coatings were then tested for bond strength. The steel HG16 grit attained the highest bond strength for the ZnAl coatings, followed by HG18 steel, HG24 steel, HG40 steel, coal slag, copper slag, and chilled iron

Future work will involve determining the relationship between other roughness attributes (e.g. peak height) and the bond strength. From the SDE methodology, grit blasting parameters can then be adjusted, optimized, and confirmed to attain the highest bond strength for A36 steel.

Acknowledgements

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