Effects of various power process parameters on deposition efficiency of plasma-sprayed Al₂O₃-40% wt.TiO₂ coatings

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Abstract. To investigate effects of various power process parameters on deposition efficiency, Al₂O₃-40% wt. TiO₂ is selected as raw material to be coated on Q235 steel substrate by air plasma spraying. Different variables of spraying current and voltage are designed, whose spraying power is from 12.8 KW to 16.8 KW and increment step is 0.8 KW. Deposition thickness is proposed as a simple method to characterize the deposition efficiency of coatings. Analysis of variance is used to observe the difference between two adjacent groups. It is shown that deposition efficiency increases with the increase of spraying current; by and large, it firstly rises and then decreases with the increment of spraying voltage. However, the effects of increasing the latter are much stronger on deposition efficiency.

Keywords: Deposition efficiency; Spraying voltage; Spraying current; Plasma spraying; Al₂O₃-40% wt.TiO₂

1. Introduction
Due to high quality of its fabricated coatings, plasma spraying is widely used in industry everywhere, such as in wear and corrosion condition. At the same time, there are tremendous advantages in deposition rate and efficiency in manufacturing [1-2]. For industrial production, economy is a factor to be seriously taken into consideration, which can be evaluated by an index called deposition efficiency (DE). However, at present, rare literatures, especially papers are publicly published on coating DE. In order to improve coating DE, a horn-section nozzle is added at the exit of spray flame, reducing the velocity of spraying flame flow and prolonging acceleration time in spraying flame [3]. On the basis of the foregoing research, the Laval nozzle structure is modified to be longer. It shows that the DE is 54% by using general plasma gun when spraying Al₂O₃-40% wt.TiO₂, however, the DE is 78% by using the improved nozzle. In other words, the DE of the latter is 44% higher than that of the former. Consequently, the porosity of the latter is 12.8%, which is 7.3% higher than that of the former [4]. Powder in the plasma flame is not fully melted may be the crucial factor responsible to low DE.

2. Experimental details
The plasma spraying equipment applied in this project is SX-80, which is the product of Guangzhou Sanxin Metal Co., Ltd., China, and the material powder is purchased from Xidao Plasma Powder Co., Ltd., China, whose size is +45-15 μm in range. Scanning electron microscope (SEM) is used to snap section pictures of coatings.
Prior to plasma spraying, necessary dressing, degreasing, blasting, roughing and cleaning are executed on Q235 steel substrate.

Deposition thickness is proposed as a simple method to characterize DE, which can be qualitative and quantitative. It is assumed that powder feeding is stable, and coating porosity is ignored.

Some process parameters are set the same, the cycles of the robot (Yaskawa), motor voltage, gas flow of powder feeding is 3 times, 3 V, 200 L/h, respectively. The hydrogen, argon gas pressure, argon gas flow, spray distance, transverse velocity of the robot is 0.70 MPa, 0.85 MPa, 1600 L/h, 100 mm, 100 mm/s, respectively.

3. Results and discussion

3.1. Effects of spraying current on DE

To investigate the effects of various current, voltage is fixed at 40 V. Differently set current is shown in Table 1.

![Figure 1. Coating section of different spraying voltage (500x).](image-url)
Table 1. Spraying current variables and explanation.

| No. | C1  | C2  | C3  | C4  | C5  | C6  |
|-----|-----|-----|-----|-----|-----|-----|
| Value/ A | 400 | 425 | 450 | 475 | 500 | 525 |

Figure 1 is sectional morphologies of C1-C6 coatings snapped by SEM in 500x scope. Thickness measurement is accomplished in digital image processing software ImageJ. To avoid measuring randomly, 15 auxiliary grid lines are added (Figure 2b), where Figure 2a is the section of C1, and measure lines are shown in Figure 2c. $\bar{x}$ is the mean value of 15 measure values, $s$ is the standard error.

![Figure 2a](image1.jpg) ![Figure 2b](image2.jpg) ![Figure 2c](image3.jpg)

Figure 2. Procedures of measuring deposition thickness.

Table 2. Thickness of spraying current group (μm).

| No. | C1  | C2  | C3  | C4  | C5  | C6  |
|-----|-----|-----|-----|-----|-----|-----|
| $\bar{x}$ | 133.54 | 134.58 | 147.68 | 149.62 | 153.91 | 184.58 |
| $s$   | 6.98  | 5.58  | 7.89  | 6.89  | 6.00  | 7.54  |

It can be seen from Table 2 and Figure 3 that coating thickness increases with the increase of spraying current, meaning deposition efficiency improves. The reason is that spraying power increases with the increase of current, and molten and semi-molten particles increase, while larger particles melt more fully, leading to higher coating deposition efficiency. At current C3-C5, it changes gradually in thickness. Molten particles compensate for the loss of vaporized particles. When it reaches C6, the mass of molten particles is much higher than that of vaporized particles.

![Figure 3](image4.jpg)

Figure 3. Effects of spraying current on deposition efficiency.

Analysis of variance (ANOVA) is used to observe difference in current variables. Firstly, normality tests in the variables are conducted, whose results are shown in Table 3. Secondly, Levene-test is used to verify whether the variance is homogeneous. The test result is 0.649, and the test of variance homogeneity passes.
Table 3. Shapiro-Wilk test.

| group | C1  | C2  | C3  | C4  | C5  | C6  |
|-------|-----|-----|-----|-----|-----|-----|
| statistic | 0.968 | 0.959 | 0.908 | 0.969 | 0.96 | 0.948 |
| P     | 0.823 | 0.668 | 0.125 | 0.842 | 0.701 | 0.491 |

Table 4. Lsd-t test of two adjacent groups.

| i  | j   | i-j  | standard error | statistic | Asp. P |
|----|-----|------|----------------|-----------|--------|
| C1 | C2  | -0.732 | 2.505          | -0.292    | 7.71e-1 |
| C2 | C3  | -13.406 | 2.505         | -5.352    | 7.44e-7 |
| C3 | C4  | -1.945 | 2.505          | -0.776    | 4.40e-1 |
| C4 | C5  | -4.290 | 2.505          | -1.713    | 9.05e-2 |
| C5 | C6  | -30.667 | 2.505       | -12.242   | 2.28e-20 |

Lsd-t test, one method of ANOVA, is used to compare difference between two adjacent groups, and results are shown in Table 4. When significance value (P, two-tailed) is less than 0.05, significant difference is observed.

From the measure values, there is no significant difference between C1 and C2 group. The possible reason is that the current is small; the energy density of plasma flame is low, only small powder is molten or partially-molten, and large powder has little positive effect on DE [5-6]. Significant difference is observed between C2 and C3 group, semi-molten and molten particles increase with the increase of current, resulting in higher DE of C3. However, DE between C3 and C4 is not significant, the possible reason is that with the increase of spraying current, the size of molten or semi-molten powder particle tends to increase, but the small powder tends to vaporize at the time, and so are C4 and C5. However, the significance between C3 and C5 is 1.48e-2, there is significant difference between the two coatings. When the variable step is small, the difference is not significant. With the interval increases, significant difference appears. And then quantitative change leads to qualitative results. With the current increasing further, more and more large-size particles become molten or semi-molten, the vaporized small-size powder is finite, contributing to higher DE. That is why the coating thickness of C6 is thicker than that of C5.

3.2. Effects of spraying voltage on DE

To investigate the effects of various voltages, current is fixed at 400 A. Differently set voltage and the coating thickness are shown in Table 5. Coating section is is shown in Figure 4.
Figure 4. Coating section of different spraying voltage (500x).

As shown in Table 6, normality tests of V1-V6 pass. The significance value of Levene test is 0.442, which indicates the variance is homogeneous. Through variance analysis, the mean square between the groups is 8363.804, group mean square is 85.410, F is 97.926, and P is 1.54e-33, intimating that all the two groups are not statistically the same. The results of Lsd-t test in Table 7 indicate that the adjacent groups are significantly different.

Table 5. Explanation and thickness (μm) of spraying voltage variables.

| voltage / V | V1   | V2   | V3   | V4   | V5   | V6   |
|-------------|------|------|------|------|------|------|
| V1          | 32   | 34   | 36   | 38   | 40   | 42   |
| mean ( )    | 139.21 | 124.52 | 157.95 | 173.33 | 190.52 | 151.64 |
| s           | 6.40 | 11.07 | 8.76 | 6.67 | 10.42 | 10.92 |

Table 6. Shapiro-Wilk test.

| group | V1   | V2   | V3   | V4   | V5   | V6   |
|-------|------|------|------|------|------|------|
| P     | 0.823 | 0.668 | 0.125 | 0.842 | 0.701 | 0.491 |

Table 7. Lsd-t analysis of two adjacent groups.

| i     | j     | (i-j)  | standard error | statistic | Asp. P     |
|-------|-------|--------|----------------|-----------|------------|
| V1    | V2    | 14.690 | 3.375          | 4.353     | 3.76e-5    |
| V2    | V3    | -33.429 | 3.375        | -9.905    | 8.96e-16   |
| V3    | V4    | -15.387 | 3.375        | -4.559    | 1.73e-5    |
| V4    | V5    | -17.189 | 3.375        | -5.093    | 2.13e-6    |
| V5    | V6    | 38.882  | 3.375        | 11.521    | 5.63e-19   |
It can be seen from Table 5 and Figure 5 that in these measure values of 6 groups from V1-V6, a tendency is shown that with the increment of spraying voltage, it firstly rises and then decreases but V2 in coating’s deposition thickness. Why V2 doesn’t obey this law is that there may be random error in experiments. The reasons are similar to those of spraying current groups. When spraying voltage reaches 40V, the deposition efficiency comes to the maximum. When spraying voltage is lifted to 42 V, the result of deposition thickness is worse than that of 40 V. Larger spraying power leads to higher semi-molten and molten degree of big-size particles; however, it exacerbates the evaporation degree of small-size and middle-size particles. At the same time, overheated particles incline to splash when impacting substrate, resulting in further mass loss in deposition process[7]. When it comes to high spraying power, agglomeration phenomenon of overheated particles occurs, attributing to low DE[8].

3.3. Difference between spraying current and voltage in affecting DE

The power increment of spraying current variable group is 0.8 KW (32V*25A=800 W), which is equal to that of spraying voltage variable group. Unlike current variable groups, the significance values of voltage variable groups are less than 0.05, so there is good reason to believe that the effect of increasing voltage is stronger than that of increasing current in the same step. Compared with spraying current groups, the peak value of DE appears earlier in spraying voltage groups. Hydrogen works as the auxiliary gas, through increasing whose gas flow, spraying voltage can be lifted. The mechanism is that hydrogen is molecule gas, whose heat transfer ability and thermal conductivity betters than that of monatomic gas. In addition, enthalpy of commonly-seen gas used in plasma spraying ranks Ar<Ar+He<Ar+H₂<N₂<N₂+H₂ in order [5].

4. Conclusions

Deposition thickness is proposed as a simple method to characterize the deposition efficiency. Conclusions can be drawn as follows.

(1) In the current variable groups, deposition efficiency increases with the increase of spraying current.
(2) In the voltage variable groups, but V2, there is a general tendency that deposition efficiency firstly increases and then decreases with the increase of spraying current.
(3) In the same step, the effect of increasing spraying voltage is stronger than that of increasing spraying current.

Acknowledgments

The authors acknowledge the financial support from Chinese National Nature Science Foundation (Grant No. 51361008) and encourage from Innovation Project of GUET Graduate Education (Project No. 2016YJCX105).
References
[1] Jia S K, Zou Y, Xu J Y, Wang J and Yu L 2015 Trans. Nonferrous Met. Soc. China 25 175-83
[2] Wang Y J, Gao B and J Y 2017 Hot Working Technology 46 42-7
[3] Schwenk A, Gruner H, Zimmermann S, Landes K and Nutsch G 2004 Improved nozzle design of de-Laval-type nozzles for the atmospheric plasma spraying Proc. of ITSC (Osaka) pp 600-5
[4] Deng C M, Zhou K S and Liu M 2010 Chin. Surf. Eng. 23 19-23
[5] Davis and Associations 2004 Handbook of Thermal Spray Technology (USA: ASM International) ed J R Davis
[6] Song R G, Wang C and Lu G 2012 Mater. Prot. Technol. 45 58-9
[7] Lech P 2011 The Science and Engineering of Thermal Spray Coatings (Beijing: China Machine Press)
[8] Wang H J, Guo Y M and Liu M 2008 Nonferr. Metals(Extractive Metallurgy) 2008 53-6