Rare Metal Materials and Engineering
Volume 46, Issue 12, December 2017
Online English edition of the Chinese language journal

Available online at www.sciencedirect.com
ScienceDirect

Cite this article as: Rare Metal Materials and Engineering, 2017, 46(12): 3583-3588.

ARTICLE

Influence of Spray Angle on Distribution of WC-Co-Cr Coating Produced by HVOF Spraying

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Abstract: When high velocity oxyfuel (HVOF) sprays complex shape parts, it is almost impossible to maintain a fixed angle between spray flame and substrate surface. Studying the effect of spray angle on coating characteristics is necessary. The present study investigates the influence of the concave radius size on the deposition rate. As feedstock material, an agglomerated and sintered WC-10Co-4Cr powder with a size distribution of 15~45 μm was used. For the spray experiments the process parameters were held constant, while the radii were selected of 10, 15 and 25 mm in concave profile. It has been generally shown that the spray angle has a great effect on coating deposition rate. The reduction of the spray angle results in a decrease of the deposition rate. A significant degradation of the coating properties is found less to 30°. The relationship between the coating's distribution and spray angle with different curvature radius was deduced.

Key words: spray angle; thickness distribution; WC-Co-Cr coating; HVOF spraying

For many years, thermal spraying technology has proven to be one of the most widely recognized industrial solution to protect tools and functional parts against mechanical wear, corrosion, electrical and magnetic damage[1, 2]. In most cases thermal spraying technology is used to coat planar or rotationally symmetric components by a linear, multi-axis handling system or industrial robots with a simple path strategy. However, in industrial applications there are more general cases and increasing redemands for parts with more complex shape, like turbine blades or forming tools. This, in turn, leads to the challenge to produce homogeneous coatings with constant coating properties on the entire surface of parts. Besides the stable coating properties, a high dimensional accuracy of the coating deposited on functional surface are also important [3, 4]. Generally, a minimum coating thickness about 100 μm is required to provide an effective protection or function. However, an increasing coating thickness will significantly reduce the shape accuracy. As an undesired result, a heterogeneous thickness distribution would unavoidably increase the difficulty of mechanical post-processing and the cost for surface finishing. So it is crucial for thermal spraying process to analyze the influence of the components geometry on the deposition rate and the coating properties[4, 5].

When spraying parts with complex shape, in consideration of the robot's kinematic and dynamic performance, an appropriate path planning can to a great extent weaken the negative effect of handling parameters such as spray angle. Spray angle is almost impossible to realize a fixed perpendicular angle or near 90° on the whole component surface during the spray process. Spray angle has a significant effect on the deposition stage, as it controls the impact direction of the spray particle on the substrate surface as well as the accumulation of the flattened particle into the layer[6-8]. Frequently changed or minor spray angle can lead to sig-

Received date: December 14, 2016
Foundation item: the Projects of Guangdong Province and of Guangzhou City (2013B050800027, 201508030001, 2016A030312015, 201513070701024, 2016GDASPT-0206, 2016GDASPT-0317)
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nificant undesirable changes of the coating properties, like high porosity and poor cohesion [9-13]. Therefore, it is of high importance to study the influence of the spray angle on the spraying process. This can provide fundamentals to determine the process parameter tolerance to produce reproducible coatings properties.

In the present study, experiments have been conducted to investigate the angular dependence of the deposition efficiency and coating morphology under different curvature radius conditions in a HVOF spray process. The experiential fitting expression to characterize the relationship between the coating's distribution and spray angle was deduced.

1 Experiment

Circular samples with different curvature radii of 10, 15 and 25 mm in concave profile were machined from a cold-swaged rod of commercially Q235 steel. Prior to deposition, the sample surfaces were ultrasonically degreased in ethanol, and then were grit blasted with 46# zircon corundum to achieve a roughened surface at the pressure of 0.25~0.35 MPa. The agglomerated and sintered WC-10Co4Cr powder (~45 μm, Amperit 588, H. C. Starck), were selected as thermal spray material. WC-10Co4Cr coatings were obtained by high velocity oxyfuel (HVOF) spraying GTV K2 system. The same pass was fulfilled under a constant thermal spray parameter as summarized in Table 1.

As shown in Fig. 1, the spray angle is defined as the angle between the axis of the HVOF flame axis and the surface or surface tangent of the component. At position A, the spray angle is equal to 0.5π. Keeping the same spray distance, when the HVOF gun move parallel to the position B, the spray angle change to zero continuously. From position A to position B, the concave profiles arrange 6~9 equi-distributed measuring points separated by evenly divided radian. The cross-section morphologies were characterized using scanning electron microscopy (SEM, JSM-5910). The coating thickness was measured by the image analyzer (Leica DMIRM).

Table 1 HVOF parameters for WC-10Co4Cr coatings

Spray Parameter	Value
Oxygen/L·min^{-1}	900
Kerosene/L·h^{-1}	26
Nozzle/mm	150
Powder feed rate/g·min^{-1}	90
Spray distance/mm	380
Transverse speed/mm·s^{-1}	1000
Number of pass	20

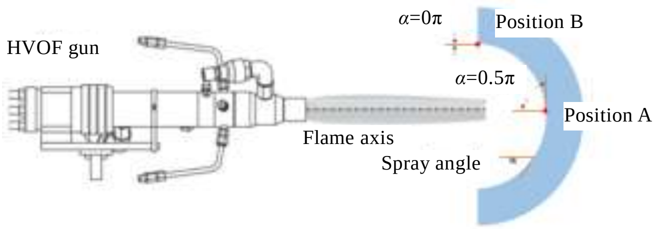

Fig. 1 Schematic graph of sample geometry and spray angle

2 Results and Discussion

2.1 Cross-section morphology of WC-10Co4Cr coatings

As shown in Fig. 2, typical WC-10Co4Cr coating were deposited on a concave profile with R_c=15 mm. Fig. 2a~2g show the cross-section microstructure of WC-10Co4Cr coatings in 7 equi-distributed spots, corresponding to different spray angle 0.5π, 0.4167π, 0.3333π, 0.25π, 0.1667π, 0.0833π and 0π, respectively. The results in Fig. 2 has proven that there is a big difference in the coating thickness at different locations on the concave surface. WC-10Co4Cr coating has the largest thickness with spraying angle 0.5π (i.e. 90°). When the spray angle becomes smaller, the WC-10Co4Cr coating thickness gradually decreases. When the spraying angle decreases below 15°, the coating is almost difficult to completely cover the substrate surface. At the spots with bigger spray angle, like the spots in Fig.2a~2d, the coatings have a high as-sprayed density with only very fine and homogenously distributed interlaminar porosity. Between the coating and substrate surface, there is no obvious porosity, indicating a good adaptation to the substrate surface. However, the coating structure becomes more inhomogeneous with the decrease of spray angle. When spraying angle drops down to 30°, some larger pores start to appear in the coating. When spraying angle drops down 15° or less, the number of holes and cracks increase in the coating. The bonding of the coating and the substrate is looser and messier, with many obvious cracks emerging at bonding locations.

2.2 Deposition thickness of WC-10Co4Cr coatings

Fig. 3 shows the relationship between the coating thickness deposited on the concave surface and spray angle. From Fig. 3, it can be seen, on the concave surface of different curvature radius, the deposited coating thickness is increased in proportion to the increase of spray angle. When R_c is 10, 15, 25 mm, the coating thickness is increased from 15 μm to about 150, 200, 220 μm, respectively. With the same spray passes, the greater the R_c, the thicker the coating indicating a higher deposition efficiency. However, with the increase of R_c, the coating thickness increase tendency becomes slow.

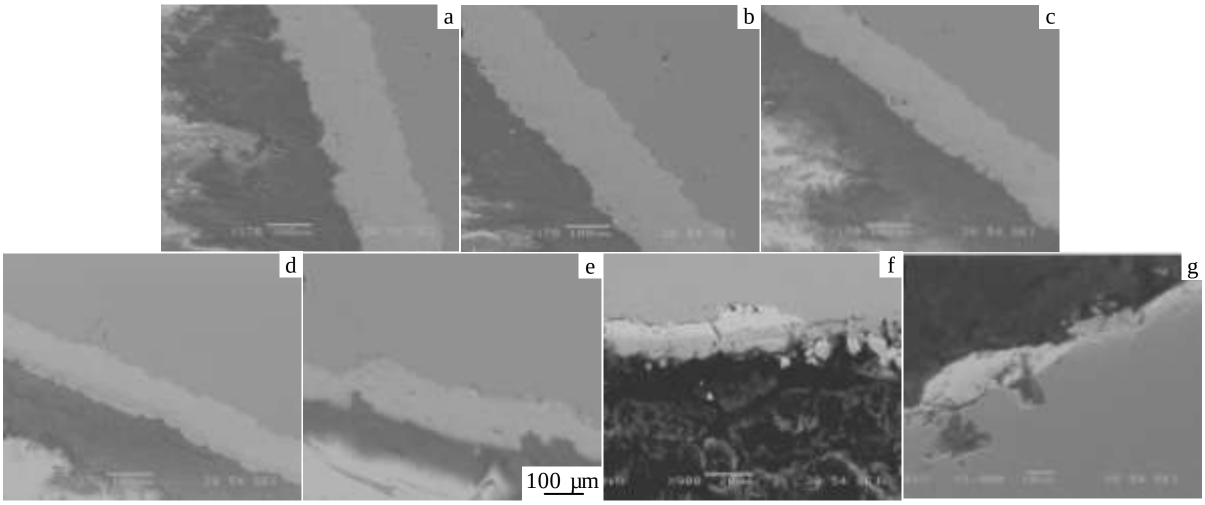

Fig. 2 Cross-section morphologies of WC-10Co4Cr coatings deposited on R_c=15 mm concave profile with different spray angle: (a) 0.5π, (b) 0.4167π, (c) 0.3333π, (d) 0.25π, (e) 0.1667π, (f) 0.0833π, and (g) 0π

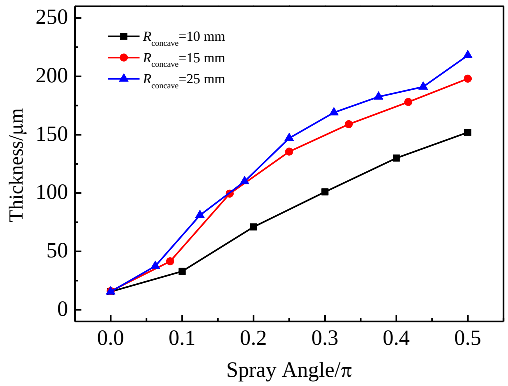

Fig. 3 Profiles of coating thickness on the concave surface

By curve fitting, as shown in Fig. 4a~4c, the relationship between the spray angle α and the thickness of coatings deposited on the concave surfaces with different curvature radius, T_{concave} can be expressed as linear quadratic equation:

$$T_{\text{concave 10}} = \frac{n}{20}(11.26786 + 298.76786\alpha - 24.10714\alpha^2) \quad (1)$$

$$T_{\text{concave 15}} = \frac{n}{20}\left(9.35892 + 588.64863\alpha - 424.3139\alpha^2\right) \quad (2)$$

$$T_{\text{concave 20}} = \frac{n}{20}\left(9.07576 + 637.72294\alpha - 458.11255\alpha^2\right) \quad (3)$$

Wherein $T_{\text{concave } R}$ is the coating thickness on concave peripheral surface with the curvature radius of R, and the unit is μm. n is the pass number of spraying. α is the spraying angle with the unit of π. The determination coefficient of fitting equation normally varies in the range of [0, 1], characterizing the quality of fit method. The determination coefficient, R-Aquare of three curves are 0.9882, 0.9846 and 0.9891, respectively. All R-Aquare values are very close to 1, showing that the fitting effect of the equations is excellent.

Therefore, the relationship between spray angle and coating thickness deposited on the concave surface with different curvature radius can be inductively expressed as a linear quadratic equation, as followed Eq.(4):

$$T_{\text{concave R}} = n(A + B\alpha - C\alpha^2) \quad (4)$$

wherein coefficient A = 0.495 0423, calculated by the averaged data. The coefficient B, C can be regressed by the Eqs.(1) ~ (3), as shown in Fig. 5.

Among them:

$$B = 32.00845 - 459.29878\mathrm{e}^{-0.32924R} \quad (5)$$

$$C = -22.94439 + 1478.40572\mathrm{e}^{-0.42196R} \quad (6)$$

By simplifying and approximating, the values or numerical expressions of coefficients A, B, C can be determined as follows:

Coefficient A is determined as 0.5, and

$$B = 32 - 460\mathrm{e}^{-0.33R} \quad (7)$$

$$C = -23 + 1500\mathrm{e}^{-0.42R} \quad (8)$$

In conclusion, the Eqs.(4), (7) and (8) can be used to determine the deposited WC-CoCr coating thickness under the reported experimental conditions with different curvature radius of concave surface, and with different spraying angle. When depositing coating on concave surface by HVOF technology, although curvature radius or spray angles are varied, the relationship between spray angle and coating thickness does not follow a linear regularity, but a quadratic regularity.

2.3 Model discussion of WC-10Co4Cr coating thickness

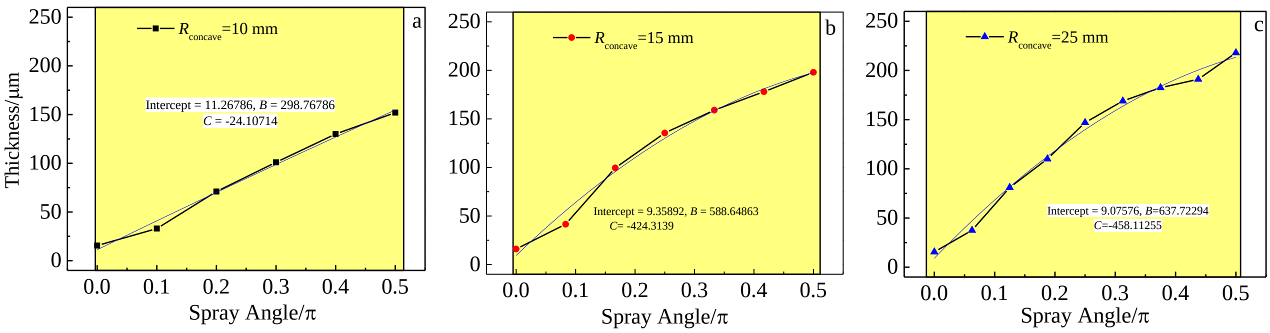

Fig. 4 Curve fitting of the relationship between spray angle and coating thickness

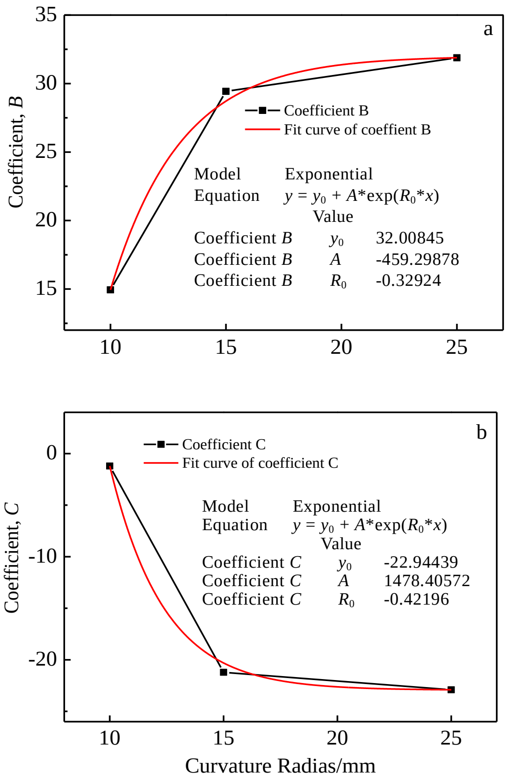

Fig. 5 Regressed coefficient *B* and coefficient *C*

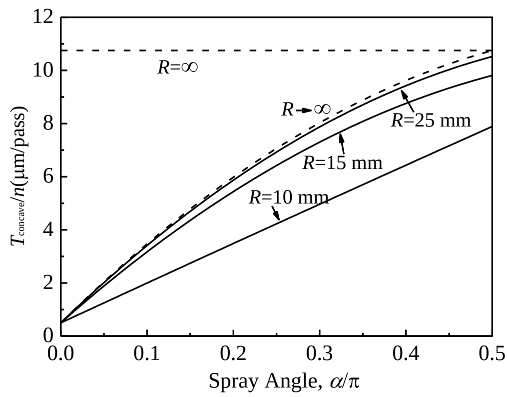

Fig. 6 Relationship graph between spray angle and coating thickness

Fig. 6 is the synthesized graph of fitted model. It's shown that when spray angle α=0, the coating deposition is almost impossible. With increasing of the spray angle, the coating thickness increases rapidly first and the increasing tendency becomes slow later. When α= 0.5, i.e. spray angle is 90°, the coating thickness t reaches the maximum.

The influence of the spray angle on coating thickness can be attributed to the ratio of tangential and normal component of the impact velocity of falling spray angles. Suppose that t is the coating thickness formed by a certain amount of spray particles with spray angle of 90°. But when the spray particles high-speed impact substrate with a spraying angle α (α<90°), the spray particle deposition speed can be decomposed along the surface normal direction and tangential direction, and the coating formation is related to movement of particle in both directions, as shown in Fig. 7. Wherein some spray particles moving along the tangential direction of the deposition surface cannot be considered depositing as a coating completely, and the other spray particles moving along the normal direction of the deposition surface deposited can be considered depositing as a coating completely. So far, the coating thickness formed by spray particle along the spray angle α (α< 90°) is $t' = t_N = t\cos\alpha$.

On the basis of Fig. 7, the primary coating model of the influence of spray angle on concave surface is proposed, as shown in Fig. 8. The deposited coating on position A on concave surface with a spraying angle α consists of three parts:

$$t_A = t_{acc,A} + t_{spu,A} + t_{reb,A} \quad (9)$$

$t_{acc,A}$ is the coating thickness entirely formed by particle accumulation. $t_{spu,A}$ is the coating thickness formed by particle sputtering from other concave locations, $t_{reb,A}$ is the coating thickness decrease formed by the rebound off of particles.

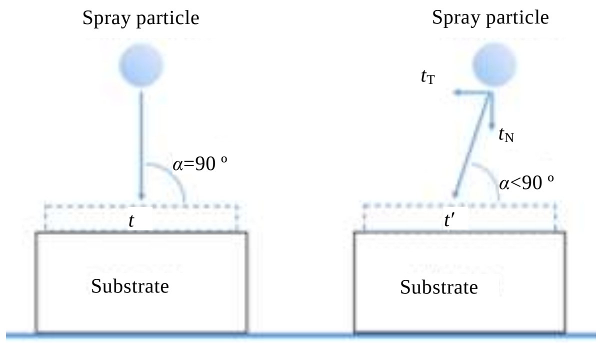

Fig. 7 Dependence of coating thickness attribute to the impact velocity component

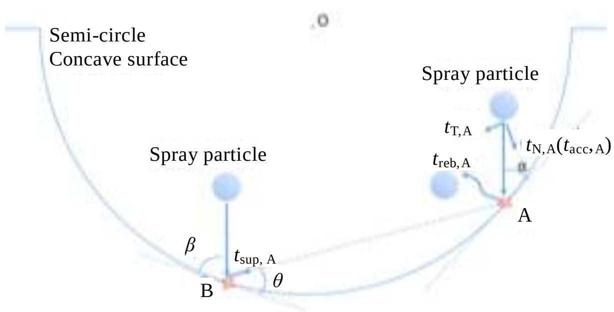

Fig. 8 Primary coating model of the influence of spray angle on concave surface

Here, $t_{acc,A}$ is a dominant factor in determining the coating thickness of position A, which are most affected by spray angle. $t_{spu,A}$ occurs mainly in the vicinity of position A. When the position B is close to position A, the influence of $t_{spu,A}$ becomes prominent. And $t_{reb,A}$ is considered as the thickness change due to particles spalling in position A, and many other complex other factors, such as grain solidification pressure, particle dynamics rebound and the flame stream erosion are involved. This is conceivable that the influence of $t_{reb,A}$ will become increasingly important as decreasing the spray angle α.

The curvature radius of concave surface of the workpiece has an obvious influence on the coating thickness. When R_c increases from 10 mm approaches to positive infinity, the deposition thickness curve of single pass gradually move towards the upper part of Fig. 7. The overall deposition efficiency of the coating is improved. When R_c approaches to positive infinity, i.e. the spray angle is 90°, single-pass deposition thickness reaches an extreme values of 10.75 μm/pass. When $R_c = \infty$, the spray substrate can be considered as a plate sample or workpiece. It's deduced that deposition efficiency of plate sample or workpiece is 10.75 μm/pass under the present experimental conditions.

When R_c increases from 10 mm approaches to infinity, the coating thickness difference of single-pass deposition is increased gradually with the increasing of spray angle. When α = 0.375, i.e. spray angle is 67.5°, the difference in thickness of the deposited coating is the largest, reaching 3.3 μm/pass. As the spray angle continues to increase subsequently, the difference in thickness of the deposited coating decreases slightly. When α = 0.5, i.e., the spray angle is 90°, the difference in deposition thickness is reduced to 2.9 μm/pass. That is, when spraying on the complex workpiece surface, the curvature radius of concave surface is changed at different location. Even if the gun axis remains perpendicular to the workpiece surface in spraying movement, i.e. spray angle remains 90°, the deposited coating thickness will vary inevitably. So, as much as possible to maintain a large spray angle can reduce the differences in coating thickness, and obtain a more uniform coating distribution. At the same time, the coating deposited using a larger spray angle will get a better performance, e.g., bonding strength and density.

It's noteworthy that when the curvature radius of concave surface is equal to 9.95 mm, the coefficient C is equal to zero and the Eq. (4) is changed to a linear equation as follows.

$$T_{\text{concave R}} = n(A + B\alpha) \tag{10}$$

In this circumstance, a straight line will be presented in Fig. 6, similar to the curve of R=10 mm. Below the straight line, i.e. the curvature radius of the concave surface is less than 9.95 mm, Eqs.(4), (7), (8) do not be applied. Moreover, smaller the data of curvature radius, the higher the variance between calculated and actual results of WC-CoCr coating thickness. The main reason is that the experiment design in this article consider three concave surface whose curvature radius are all larger than 10 mm. The relationship between spray angle and coating thickness induced by these three concave surface with large curvature radius, of cause, has the limited apply range. When R_c = 10 mm approaches to positive infinity, the curve can be extended to apply, but from R_c = 10 mm extended to zero, the curve is not applicable for two reasons. The first, when the curvature radius of the concave surface is greatly reduced, the turbulent flow of spray flame near the substrate surface and the disorderly rebounce of spray particle are more obvious due to the special geometry nature of concave profile. This is a significant predominant factor to determine the deposition method and coating growth. It can be inferred that the coating thickness will increase with the increasing of spray angle under a small curvature radius on concave surface, but the regularity will not simply follow the quadratic curve. The second, when the curvature radius is smaller than 10 mm, the concave surface can be considered as a small pit on workpiece surface and be completely covered in the central region of the spray flame. The coating in concave pit accumulate too fast to characterize and analyze. In this case, whether the powder materials is uniformly distributed in the HVOF flame will be an important factor which cannot be ignored. When R_c is very small corresponding to the size of flatten particles, it's almost impossible to conclude an empirical regularity by way of spray experiment.

3 Conclusions

1) The spray angle has a great effect on coating deposition rate. The reduction of the spray angle results in a decrease of the deposition rate. A significant degradation of the coating properties was found less to 30 °.

2) The relationship between the coating's distribution and spray angle with different curvature radii under the reported experimental conditions is deduced as:

$$T_{\text{concave } R} = n(A + B\alpha - C\alpha^2)$$

wherein the coefficient A is determined as 0.5, and

$$B = 32 - 460e^{-0.33R}$$

$$C = -23 + 1500e^{-0.42R}$$

In conclusion, when depositing coating on concave surface by HVOF technology, although curvature radii are different, the relationship between spray angle and coating thickness does not follow a simple linear regularity, but a quadratic regularity which need be modified according to spraying parameters and spray materials.

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喷涂角度对 HVOF WC-Co-Cr 涂层分布的影响

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摘 要：在喷涂复杂形状部件时，高速氧燃气 (HVOF) 喷涂 焰流和基体表面几乎不可能固定一个角度。研究喷涂角度对涂层性质的影响是必要的，并研究了凹面曲率半径对沉积率的影响。实验使用团簇烧结的 WC-10Co-4Cr 粉末（粒度 15~45 μm）。实验时喷涂参数不变，喷涂半径为 10, 15, 25 mm 的凹面。结果表明，喷涂角度严重影响涂层沉积率。喷涂角度减小导致沉积率减少。当喷涂角度小于 30 °，涂层性质显著降低。涂层沉积分布和不同凹面半径的关系被推导。

关键词：喷涂角度；厚度分布；WC-Co-Cr涂层；HVOF 喷涂

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