Study on Effect of Evaporation Source Position on Film Thickness Uniformity of Vacuum Coating Equipment

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***Abstract*—The uniformity of the film thickness is an important index to evaluate the performance of coating equipment. It is essential to determine the optimal position of the evaporation source rapidly and accurately for improving the uniformity of film thickness. The conventional equipment debugging method mainly adopts the combination of experience and experiment. But it is not only unable to reach the optimized state but also time-consuming and laborious. To address this problem, an analytical optimization method is proposed. At first, by establishing a geometric model of the coating machine, the theoretical mathematical model of film thickness and uniformity is derived. Second, the distribution curve of film thickness and uniformity is calculated and simulated so that how to find the best curve is transformed into a convex optimization problem. Finally, the optimal position of evaporation source is solved by Particle Swarm Optimization algorithm, and the control of the film thickness is achieved quickly and accurately.**

Keywords—uniformity of the film thickness; coating machine; convex optimization; particle swarm optimization

I. INTRODUCTION

The uniformity of film thickness in the vacuum coating process is the main basis for measuring the quality of the coating equipment and the coating products, so it plays plays an important role in the field of vacuum coating [1-6]. There are many factors affecting the film thickness uniformity, such as the temperature control of heating, the structure of evaporation source, the geometric configuration of coating system, the shape of clamp, the movement mode of substrate ,etc[7-13]. In this paper, to address the evaporation coating equipment, considering the structural factors of the coating equipment itself[14], through modeling, calculation, derivation, computer-aided simulation and particle swarm optimization algorithm, we can quickly find the optimal location of the evaporation source. After comprehensive consideration, the specific position of the evaporation source can be finally determined by taking the film thickness curve that can reflect the material utilization rate as reference. It provides a theoretical basis for the subsequent production,R&D and design. The overall research process is shown in figure 1:

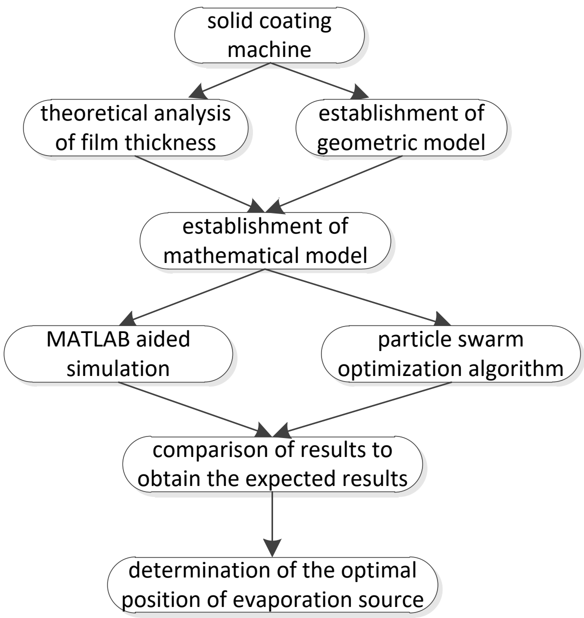

Figure 1 Overall Design Process

II. THEORETICAL ANALYSIS OF FILM THICKNESS

This study and the calculation of mathematical models[15-16] is based on the following ideal assumptions:

- There is no collision between evaporated organic liquid molecules due to irregular movement,and there is no collision between organic liquid molecules and residual gas due to irregular movement
- When the evaporated organic liquid molecules reach the surface of the substrate, they all precipitate

to form a tightly structured film, which is the same as the density of the bulk material. That is to say, the adhesion coefficients are all 1;

- The emission characteristics of evaporation sources are stable, which means they do not change with time.

Based on the above assumptions, the approximate distribution of film thickness can be calculated by determining the parameters between evaporation source and substrate and coating. Early studies have shown that evaporation sources can be roughly divided into three categories: point source, surface source and linear evaporation source. As this experiment uses a small-surface evaporation source, thus this study will not give too much description on point evaporation source and linear evaporation source. The study shows that the vapor emission characteristics of surface evaporation source follow the law of cosine distribution, In other words, the vapor density is distributed in cosine according to the Angle between the set direction and the surface. In the theoretical calculation of this paper, the geometric distribution model of film thickness with emission characteristic n=1 is only discussed.

It is assumed that the total amount of charge in the crucible is m, all the amount of m evaporating within a certain time t, In that way can the evaporation efficiency be 100%. Then the total amount of coating material deposited in the three-dimensional angle dω of the vertical angle α from the emission surface of the evaporation source is dM, with the coating plane corresponding to dω being ds. As shown in Figure 2[16], the small plane ds with an angle of θ between the evaporation distance r and the evaporation direction is inclined. The resulting solid angle dω is:

$$d\omega = \frac{ds \cdot \cos\theta}{r \wedge 2} \tag{1}$$

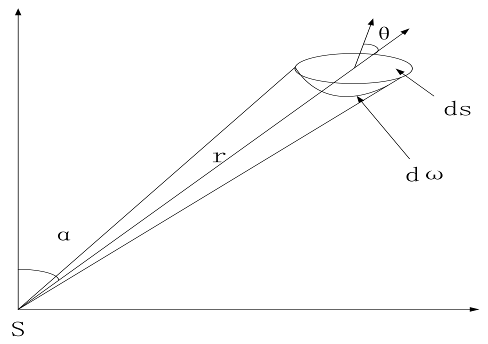

Figure 2 Angle Relation

Because the small surface evaporation source is adopted, the small surface evaporation source follows the cosine law, Meanwhile, its steam emission characteristics are directional, which leads to the evaporation material in dω being:

$$dM = f \cdot \cos\alpha \cdot m \cdot d\omega = \frac{f \cdot m \cdot ds \cos\alpha \cos\theta}{r \wedge 2} \tag{2}$$

In the formula, with f being the proportional constant., the integral constant f can be calculated by integrating on the whole receiving surface. Letting the receiving surface be a sphere, the evaporation source is on the center of the sphere, so $\theta = 0$, $ds = 2\pi r \wedge 2 \sin\alpha d\alpha$. Because the emission limit of the small surface evaporation source is a hemisphere, it can be integrated on the hemisphere:

$$\int dM = f \cdot m \cdot \int_0^{\frac{\pi}{2}} 2\pi \cos\alpha \sin\alpha d\alpha \tag{3}$$

Resulted in $f = \frac{1}{\pi}$, so

$$dM = \frac{1}{\pi} m \cos\alpha \cdot d\omega = \frac{m \cdot \cos\alpha \cos\theta}{\pi r \wedge 2} ds \tag{4}$$

Set the film thickness is t and the density is ρ , then

$$dM = \rho \cdot t \cdot ds \tag{5}$$

The film thickness [15-16] is

$$t = \frac{dM}{\rho \cdot ds} = \frac{m \cdot \cos\alpha \cos\theta}{\pi \cdot \rho \cdot r \wedge 2} \tag{6}$$

III. GEOMETRIC MODEL AND MATHEMATICAL MODEL OF FILM THICKNESS DISTRIBUTION OF CIRCULAR TOP SUBSTRATE SUPPORT FRAME

A. Geometric Model of Circular Top Substrate Support Frame

There are many kinds of substrate support frames to improve the uniformity of film thickness, different forms of substrate supports have different effects on it. In this paper, only the circular top substrate support frame is studied.

Let the curvature radius of the circular top substrate support frame be R, the spherical center be b, the distance between the evaporation source and the center of the coating cavity be q, the vertical height from the center of substrate support frame to the evaporation source be h, the distance from any point P on the substrate to the center of the coating cavity be a, the azimuth angle be φ, the evaporation source be s, the distance between evaporation source and point p on the substrate be r, the angle between the connection between the p point and the c point and the z axis be β, as shown in Figure 3:

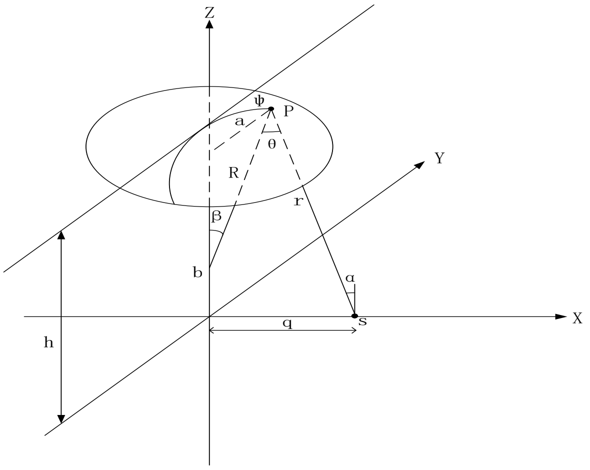

Figure. 3 Circular top substrate support frame

B. Mathematical Model of Film Thickness Distribution of Circular Top Substrate Support Frame

The uniformity is represented by the ratio of film thickness at any point on the substrate to the film thickness at the center point of the substrate. If t_0 is the film thickness at the center point of the circular top support frame , t is the film thickness at p-point with a distance a from the center point; Then t/t0 can be used to measure the film thickness uniformity at each point relative to the center point of the support surface of the dome substrate in this paper. If this ratio is closer to 1, the more uniform the film thickness on the substrate is, the farther away it is and the more uneven the film thickness on the substrate is. If it is reflected on the curve or surface, the closer the curve to the straight line and the surface to the plane are, the more uniform the film thickness is, then the film thickness at any point on the substrate is as follows:

$$t=\frac{m\cdot[h-R(1-\cos\beta)]\cdot\left[R-R\cos\beta+h\cos\beta-q\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]}{\pi\cdot\rho\cdot\left[h\wedge2+q\wedge2+(2R\wedge2-2hR)(1-\cos\beta)-2qR\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]\wedge2} \quad (7)$$

The thickness of the film at the center of the substrate is as follows:

$$t_0=\frac{m\cdot\cos\alpha\cos\theta}{\pi\cdot\rho\cdot r\wedge2}=\frac{m\cdot h\wedge2}{\pi\cdot\rho\cdot(h\wedge2+q\wedge2)\wedge2} \quad (8)$$

Because the circular top substrate support frame rotates rapidly in the working process, the ratio of the actual p-point film thickness to the film thickness of the dome center point is:

$$\frac{t}{t_0}=\frac{\int_0^{2\pi}\frac{m\cdot[h-R(1-\cos\beta)]\cdot\left[R-R\cos\beta+h\cos\beta-q\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]}{\pi\cdot\rho\cdot\left[h\wedge2+q\wedge2+(2R\wedge2-2hR)(1-\cos\beta)-2qR\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]\wedge2}d\varphi}{\int_0^{2\pi}\frac{m\cdot h\wedge2}{\pi\cdot\rho\cdot(h\wedge2+q\wedge2)\wedge2}d\varphi} \quad (9)$$

IV. Computer Simulation of Film Thickness Distribution

A. Analogy Method

From the derived formula (9), it can be seen that a set of a is taken to obtain a distribution curve of film thickness when the parameters h and R of the coating equipment are known and the q value is fixed. The smoothest and flattest curve or surface can be found out from countless sets of curves or surfaces which are produced with the different q, meanwhile, the corresponding value of q is the optimal position of the evaporation source that we need to determine. How to find the best curve can be transformed into a convex optimization problem so that the optimal position of evaporation source can be solved by the particle swarm optimization algorithm to determine .

Particle Swarm Optimization, also known as Particle Swarm Optimization Algorithm or Bird Swarm Foraging, is abbreviated to PSO. Like most algorithms, the globally optimal solution can be found through the locally one which is find by iterative method from the objective function. But it is easier and faster to realize, which have high location accuracy and fast convergence speed. It has great advantages in solving practical problems.

B. Computer Simulation Results of Film Thickness Distribution

The vertical height from the basic center of a certain type of coating machine to the evaporation source is h=1400, the curvature radius of the circular top substrate support frame is R=1500, the distance from any point on the substrate to the center is a, the initial value is 0, the step size of 20 is gradually increased, and a series of points are obtained.

The fitting curve of film thickness under different q values are shown in Figure 6. From the simulation results, it can be seen that the film thickness decreases with the increase of q value, that is, the farther away the evaporation source is from the center of the substrate, the lower the material utilization ratio is, because economically, not only the uniformity of film thickness should be considered, but also the utilization ratio of materials and the cost can be reduced. The result diagram of film thickness variation is used as a reference to determine the optimal q value of film thickness uniformity.

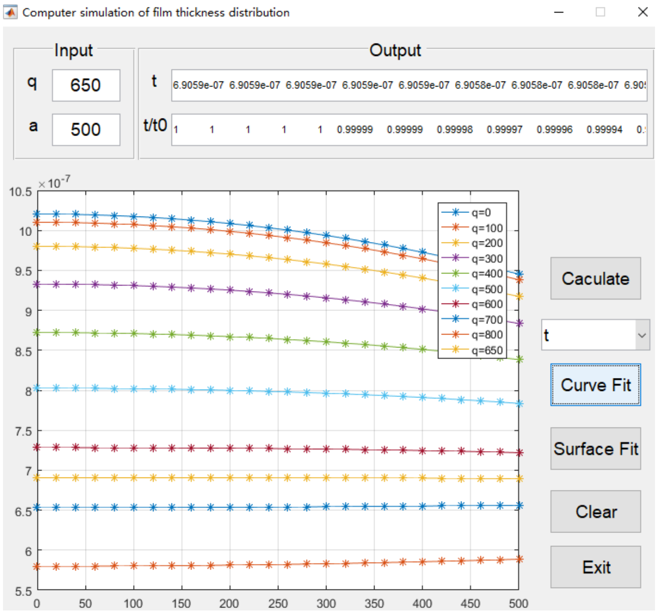

Figure. 6 Fitting diagram of film thickness curve under different evaporation source position

The uniformity curve of film thickness under different q values are shown in Figure. 7. It can be seen from the result diagram that with the increase of q value, the uniformity curve of film thickness becomes smooth at first, then becomes steep after reaching a certain value, that is to say,the uniformity of film thickness becomes better at first and then worse with the increase of Q value. When q=650 or so, the uniformity curve of film thickness is the best and the film thickness is the most uniform.

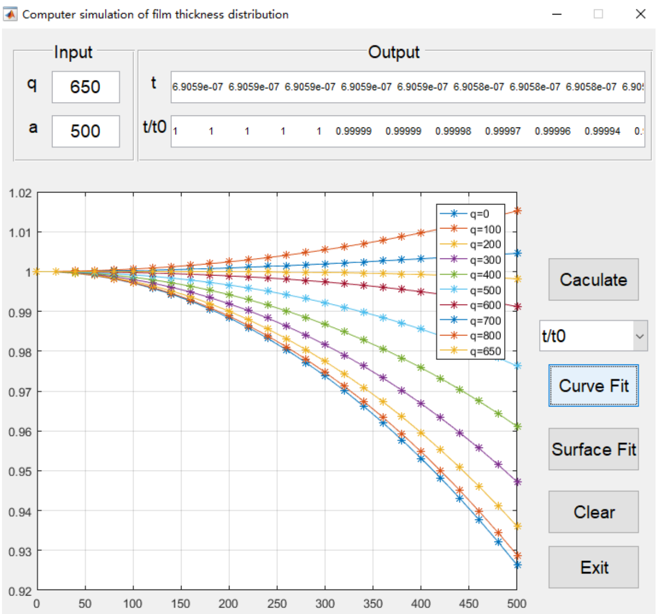

Figure. 7 Simulation diagram of film thickness uniformity curve under different evaporation source position

C. Iterative Results of Particle Swarm Optimization

The above mathematical model can be expressed as follows:

$$\sin\beta = \frac{a}{R} \qquad (10)$$

$$\cos\beta = \sqrt{1-\left(\frac{a}{R}\right)^{\wedge}2} \qquad (11)$$

$$F(a)=\frac{t}{t_0}=\frac{\int_0^{2\pi}\frac{m\cdot[h-R(1-\cos\beta)]\cdot\left[R-R\cos\beta+h\cos\beta-q\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]}{\pi\cdot\rho\cdot\left[h^{\wedge}2+q^{\wedge}2+(2R^{\wedge}2-2hR)(1-\cos\beta)-2qR\sin\beta\cos(\frac{\pi}{2}-\varphi)\right]^{\wedge}2}d\varphi}{\int_0^{2\pi}\frac{m\cdot h^{\wedge}2}{\pi\cdot\rho\cdot(h^{\wedge}2+q^{\wedge}2)^{\wedge}2}d\varphi} \qquad (12)$$

The objective function is:

$$\min\ \sqrt{\frac{\sum_{i=1}^{n}\left(F(a_i)-\bar{F}(a)\right)^2}{n-1}}$$

(13)

That is to say, it is necessary to optimize the objective function. In this function, h=1400, R=1500, what needs to be sought is a minimum q to minimize the objective function.

The flow of particle swarm optimization algorithm for this example is as follows:

Step 1: Set the size of the particle group and select the number of particles to be 50, because there is only one parameter to be optimize so that each particle has only one-dimensional vector of position and speed.

Step 2: In the initialization range, the position and speed of the particle swarm are initialized Randomly.

Step 3: Calculate the fitness value of each particle, that is, evaluate the objective function.

Step 4: Update the historical optimal position of the particle individual.

Step 5: Update the historical optimal position of the particle population.

Step 6: Update the speed and position of the particles, the formula is as follows:

$$v_{k+1} = c_0 v_k + c_1\xi(p_k - x_k) + c_2\eta(p_g - x_k) \qquad (14)$$

$$x_{k+1} = x_k + v_{k+1} \qquad (15)$$

Among them, inertia factor c0take 1, part of the learning factor of self-cognition c1 take 2, part of the learning factor of social experience c2 take 2.

Step 7: If the termination condition is not met, turn to step 3.

Based on the above process, the optimization simulation of the objective function is carried out, the maximum number of iterations is 1000 and the minimum q is 656.1822. Compared with the previous results, it is in line with the expected value.

V. CONCLUSION

The specific location of the evaporation source with the best uniformity of film thickness is determined in this paper. First, the simplified geometric model of the evaporation solid plating machine is established, meanwhile, the mathematical method is used to model, deduce and analyze it. Second, the distribution curve of film thickness and uniformity is calculated and simulated by using MATLAB software and the particle swarm optimization algorithm is used to solve the objective function iteratively. Finally, compare the simulation results with the results obtained by particle swarm optimization algorithm. According to the theoretical optimal q value, the specific position of the evaporation source with the best uniformity of film thickness is obtained. It provides a vital reference for later R&D and production.

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