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Analysis of Several Key Parameters in the Design of Infrared Stealth Coating

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Abstract. In order to optimize the design and further determine the related parameters of the infrared stealth coating, this thesis derives the calculating formula of coating thickness ***d*** and surface emissivity ***ε*** based on optical thin film theory and conducts relevant designing targeted at multi-layer spraying existing in the stealth coating operations. The research results show that the proposed method extends the application of optical thin film theory in stealth coating designing and has theoretical significance for the future research of stealth coating.

1 Introduction

With the development of modern military infrared reconnaissance and detection technologies, especially the extensive use of thermal infrared homing guided weapon system, the possibilities that various types of military targets and weapons are spotted in the battle field and thus were destroyed turn out to be higher and higher. Under such circumstances, our military equipment including aircraft, tanks and vehicles are required not only with sound accuracy and maneuverability but also with outstanding concealment. Facing the big challenge of how to effectively minimize and avoid the possibility our military targets being spotted, the infrared stealth coating technology is a simple and economical approach which is easy to be carried out [5~8].

The core evaluation parameter of infrared stealth coating is generally surface emissivity ε [9~11], which is obtained from surface reflectivity R concluded through radiation transfer equation based on Kirchhoff's law. As the solution of the radiation equation is difficult in practical calculation, researchers tend to adopt multi-flow theory [12] instead which still requires a huge workload. To make it easy for calculation，the adoption of optical thin film design theory can facilitate the calculation of several key parameters in infrared stealth coating design and offer a fresh-new method for determining ε .

2 Determination of the Relationship between Filler and Base Material of Infrared Stealth Coating

The infrared stealth coating is generally composed of fillers, pigments and binders [13]. Without regard to the compatibility with visible light, the biggest influence on the infrared surface emissivity is the filler and binder, among which the emissivity of the binder is the definite value. Thus, the determination of the relationship between fillers' surface emissivity and matrix carries great significance. According to the refractive index matching conditions, when the infrared radiation is incident at a certain angle of inclination, the effective refractive index of component ***P*** and component ***S*** on different refractive index material interface is:

$$\eta_p = N/\cos\theta$$
$$\eta_s = N\cos\theta \tag{1}$$

Where:

η refers to the effective refractive index;

N refers to the refractive index of the incident material;

θ refers to the angle of incidence; degree.

Due to the different effective refractive index and reflection coefficient, the separation of the spectral reflectance (or transmittance) curve of component ***P*** and component ***S*** tends to occur and thus polarization effect may happen. On the interface of two kinds of refractive indexes n_H and n_L , when the incident angle satisfies the Brewster angle, the reflection of ***P*** polarized light is zero and there is partial reflection in ***S*** polarized light. In order to increase the reflectivity of ***S*** polarized light and to make the transmittance of ***P*** polarized light close to 1, two kinds of materials may be made into a multi-layer coating system to achieve the greatest degree of infrared stealth effect.

From Fresnel Principle, the relationship of the reflection coefficient of component ***P*** between the two materials with the refractive index of n_H and n_L is as follows:

$$r_{HLP} = \frac{n_H / \cos\theta_H - n_L / \cos\theta_L}{n_H / \cos\theta_H + n_L / \cos\theta_L} \tag{2}$$

Where:

θ_H and θ_L are the refraction angles where the light is at high and low refractive index coating of n_H and n_L .

If

$$n_H / \cos\theta_H = n_L / \cos\theta_L \tag{3}$$

Then

$$r_{HLP} = 0 \tag{4}$$

Assume that the angle of incidence of infrared radiation at the coatings is θ_0, and the refractive index of the base material is n_G .

$$\cos\theta_H = \left[1 - (n_G / n_H)^2 \sin^2\theta_0\right]^{1/2}$$
$$\cos\theta_L = \left[1 - (n_G / n_L)^2 \sin^2\theta_0\right]^{1/2} \tag{5}$$

Introduce(5) into(3):

$$n_G \sin\theta_0 = \frac{n_H n_L}{(n_H{}^2 + n_L{}^2)^{1/2}} \tag{6}$$

It can be concluded from (6) that there is relationship between base material and the conditions that the high and low refractive index (filler) shall meet and there is relationship between the refractive index n_G of matrix material and the determination of angle of incidence θ_0 .

$$\begin{cases} n_H d_H = \dfrac{\frac{\lambda_{\text{Incident}}}{4}}{\sqrt{1 - n_0^2 \sin^2\theta_0 / n_H}} \\ n_L d_L = \dfrac{\frac{\lambda_{\text{Incident}}}{4}}{\sqrt{1 - n_0^2 \sin^2\theta_0 / n_L}} \end{cases} \Rightarrow \begin{cases} d_H = \dfrac{\frac{\lambda_{\text{Incident}}}{4}}{\sqrt{n_H^2 - n_0^2 \sin^2\theta_0}} \\ d_L = \dfrac{\frac{\lambda_{\text{Incident}}}{4}}{\sqrt{n_L^2 - n_0^2 \sin^2\theta_0}} \end{cases} \tag{9}$$

where:

d_H and d_L refer to high and low geometrical thickness; μm

λ refers to the wavelength of incident light; μm .

According to the computational formula of the thickness d of the coating deduced from refractive index matching condition (6) and phase matching conditions (8), as the atmospheric infrared window is composed of three bands, the corresponding thickness is also quite different.

When the angle θ_0 is equal to $90°$, the value of n_G is maximum.

Then

$$n_G = \frac{n_H n_L}{(n_H{}^2 + n_L{}^2)^{1/2}} \tag{7}$$

Metal materials such as aluminum, aluminum alloy plate and iron plate are the common matrix materials. So the value of n_G is known which provides theoretical basis for the selection of the fillers at the early stage of the test and which provides a convenient method for the selection of some organic materials.

3 Determination of Thickness of Infrared Stealth Coating

Thickness value of infrared stealth coating ranges between 0~100 μm . Based on the vector calculation results of optical thin film, the coating is designed as $\lambda/4$, that is, the thickness in each layer is $\lambda/4$ and the selected coating thickness is ***S*** (The reflectivity increase with the increase of the number of layers)to make the reflected light interfere. With appropriate number of layers, ***S*** component of the incident beam reflects and the thickness is supposed to satisfy the condition:

$$n_H d_H \cos\theta_H = n_L d_L \cos\theta_L = \frac{\lambda}{4} \tag{8}$$

Hence, the whole coating is retained at an odd number of layers, but the equivalent thickness of the whole coating is the integer multiples of $2/\lambda$. Thus, the infrared stealth coating is achieved where the component ***S*** is reflected and component ***P*** is all through.

The thickness of each layer is:

4 Determination of Reflectivity of Infrared Coating

Assume that the number of layers of multiple coatings is 2n+1 (n=0,1,2,3,……)and the thickness is $\lambda/4$, According to EM theory, the characteristic matrix of coating is:

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} 0 & i/\eta_H \\ i\eta_H & 0 \end{bmatrix} \begin{bmatrix} 0 & i/\eta_L \\ i\eta_L & 0 \end{bmatrix} \begin{bmatrix} 0 & i/\eta_H \\ i\eta_H & 0 \end{bmatrix} \mathrm{L\ L} \begin{bmatrix} 0 & i/\eta_H \\ i\eta_H & 0 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_G \end{bmatrix} \tag{10}$$

where:

η_H is the effective refractive index of high refractive index coating;

η_L is the effective refractive index of low refractive index coating;

η_G is the effective refractive index of base material.

$$\begin{bmatrix} B \\ C \end{bmatrix} = \begin{bmatrix} 0 & i^{2n+1}\eta_L^n/\eta_H^n \\ i^{2n+1}\eta_L^n/\eta_H^n & 0 \end{bmatrix} \begin{bmatrix} 1 \\ \eta_G \end{bmatrix} = \begin{bmatrix} i^{2n+1}\eta_L^n\eta_G/\eta_H^n \\ i^{2n+1}\eta_L^n/\eta_H^n \end{bmatrix} \quad (11)$$

The equivalent refractive index of the coating is:

$$Y = \frac{C}{B} = \frac{\eta_H^{2n+2}}{\eta_L^{2n}\eta_G} \quad (12)$$

The reflectivity of the coating is:

$$R = \left(\frac{\eta_G - Y}{\eta_G + Y}\right)^2 = \left(\frac{\eta_G - \eta_H^{2n+2}/\eta_L^{2n}\eta_G}{\eta_G + \eta_H^{2n+2}/\eta_L^{2n}\eta_G}\right)^2 \quad (13)$$

$$\eta_G = \eta_H = \eta_L = n_G / \cos\theta_G \left(n_0 = n_G\right) \quad (14)$$

When the light is tilted, the effective refractive index of each layer of the S polarization component is:

$$\begin{cases} \eta_G = n_G \cos\theta_G \\ \eta_H = n_H \cos\theta_H \left(n_0 = n_G\right) \\ \eta_L = n_L \cos\theta_L \end{cases} \quad (15)$$

As for P polarization component, introduce (14) into (12):

$$R_P = \left(\frac{\eta_G - \eta_H^2/\eta_G}{\eta_G + \eta_H^2/\eta_G}\right)^2 = \left[\left(\frac{n_G^2\cos\theta_H}{n_H^2\cos^2\theta_G} - 1\right) \Big/ \left(\frac{n_G^2\cos\theta_H}{n_H^2\cos^2\theta_G} + 1\right)\right]^2 \quad (16)$$

As for S polarization component:

$$R_s = \left[\frac{n_G^2\cos^2\theta_G - (n_H\cos\theta_H)^{2n+2}/n_G\cos\theta(n_L\cos\theta_L)^{2n}}{n_G^2\cos^2\theta_G + (n_H\cos\theta_H)^{2n+2}/n_G\cos\theta(n_L\cos\theta_L)^{2n}}\right]^2 \quad (17)$$

It can be obtained from (3):

$$\frac{n_H\cos\theta_H}{n_L\cos\theta_L} = \frac{n_H^2}{n_L^2} \quad (18)$$

Introduce into (16), then:

$$R_S = \left[\frac{n_G^2\cos^2\theta_G - (n_H\cos\theta_H)^2 n_H^{4n}/n_G n_L^{4n}}{n_G^2\cos^2\theta_G + (n_H\cos\theta_H)^2 n_H^{4n}/n_G n_L^{4n}}\right]^2 \quad (19)$$

It can be simplified into:

$$R_S = \left[1 - \frac{2n_G^2\cos^2\theta_G}{n_G^2\cos^2\theta_G + \dfrac{n_H^2\cos^2\theta_H}{n_G}\left(\dfrac{n_H}{n_L}\right)^{4n}}\right]^2 \quad (20)$$

It can be concluded from (15) that as long as the Brewster angle conditions are met, P polarized light reflectivity has nothing to do with the number of layers but depends on refractive index of coating and base material; It can be concluded from (19) that the reflectivity of infrared stealth coating depends on the layer $2n+1$, among which the value of n bigger, the R_s bigger.

Thus, the reflectivity of infrared coating is:

$$R = \frac{1}{2}(R_s + R_p) \quad (21)$$

5 Determination of Surface Emissivity ε of Coating

According to Kirchhoff's law:

$$\varepsilon = 1 - R = 1 - \frac{1}{2}(R_s + R_p) \quad (22)$$

$$\varepsilon = 1 - \frac{1}{2}\left[\frac{\left(\dfrac{n_G^2\cos\theta_H}{n_H^2\cos^2\theta_G} - 1\right)}{\left(\dfrac{n_G^2\cos\theta_H}{n_H^2\cos^2\theta_G} + 1\right)}\right]^2 - \frac{1}{2}\left[1 - \frac{2n_G^2\cos^2\theta_G}{n_G^2\cos^2\theta_G + \dfrac{n_H^2\cos^2\theta_H}{n_G}\left(\dfrac{n_H}{n_L}\right)^{4n}}\right]^2 \quad (23)$$

The ε of infrared stealth coating depends on n , for the bigger the n , the bigger the valve of ε and the calculation of ε can be achieved through ***Matlab*** procedure. Through the combination of theory and experiment, the target surface emissivity ε can be determined which is accompanied by the optimal number of layers.

6 Conclusion

Infrared radiation, like X rays, radio waves and light waves is also one form of electromagnetic waves but with different frequencies. So the theory of physical optics is also applicable to infrared radiation, that is, the interference, diffraction and polarization of light wave in the transmission process also exist in infrared radiation.

In general, when the organic compound is used as fillers, the molecular vibration and rotation of its functional groups are the main factors to be considered . According to the relationship between the filler and the base of the infrared camouflage coating derived from refractive index matching conditions, when the angle of incidence is 90 degree and the material value of the base material n_G is known, it can provide a convenient method for the selection of organic materials.

The layers n of infrared stealth coating are mostly determined by the experimental results and in the calculation formula that deduces the target surface emissivity ε, the optimal layers can be theoretically determined from the above formula.

In conclusion, it is theoretically feasible for this thesis to conduct the calculation of several key parameters in the design of infrared stealth coating by adopting the optical thin film theory. The components mentioned hereinabove constitute the design basis and offers a new method for determining ε, posing theoretical guidance for the future research of stealth coating.

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