A research on the spectral Bidirectional Reflectance Distribution Function measurement of tensile polyimide film rough surfaces

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Abstract: The reflection distribution function is important for calculating the scatter distribution on material surface. In order to calculate the light scatter distribution of the tensile polyimide, it is necessary to investigate the relationship between the Bidirectional Reflectance Distribution Function (BRDF) of tensile polyimide film with its surface roughness and the incident light, and test the fitting function to evaluate the BRDF. The measurement spectrum is from 300nm to 750nm. The measurement results show that the BRDF of polyimide film are different with the tensile stress, and the reflectance intensity in the reflective direction decreases with the increase of the tensile stress, increases with the wavelength of the incident light. The reflectance intensity is associated with the roughness changing of polyimide surfaces for the tensile stress, as the roughness increases with the more stress, and the intensity increases in the none reflective direction. The fitting precision is up to 95% applying with the T-S model compared with the classical Phong model. The research data can be used to evaluate the reflective intensity of pharmaceutical packaging film, medical light barrier film, thermal insulation film and other film materials.

1. Introduction
Polyimide film is comment used in industry and used as optical material especially. Tension film is often used in astronomical telescope to block stray light. James Weber of American space telescope uses tension film to block stray light from the earth. The light blocking effect of the film is achieved by reflecting the incident light from the surface. The light blocking effect is evaluated by the surface scattering characteristics, and generally characterized by the bidirectional reflectance distribution function. The reflection distribution function is important for calculating the scatter distribution on material surface. The Bidirectional Reflectance Distribution Function (BRDF) is used to describe the reflection characteristics of the rough surface\textsuperscript{[1]}. BRDF is used to describe the stray radiation of open surface,\textsuperscript{[2]} the stray light distribution inside the channel,\textsuperscript{[3]} the solar light scattering characteristics of satellite surface,\textsuperscript{[4-5]} and the infrared reflection characteristics of heat preservation material surface\textsuperscript{[6]}. The Polyimide film is often stored in freedom stage while used with tensile stage. In order to calculate the light scatter distribution of the tensile polyimide, it is necessary to investigate the relationship between the BRDF with the rough value and the incident angle, and test the fitting function to evaluate the BRDF.
The research of BRDF mainly focuses on satellite coating film and coating film. Liu Chen Hao analyzed the measured BRDF and the limitations in Phong model, and gave a modified model which described the Fresnel reflection properties\cite{7}. Yang Fan analyzed the surface infrared characteristics of aluminized polyimide film by the Torrance-Sparrow bidirectional reflectance distribution function.\cite{8} Fontanot present a combined morphological and BRDF characterization of Al-coated thermoplastic polymer surfaces.\cite{9} Yang PY report the Bidirectional reflection of semitransparent polytetrafluoroethylene (PTFE) sheets on a silver film\cite{10}. Prater W set up surface scanning inspection system particle detection dependence on aluminum film morphology.\cite{11} Li Q researched on the light scattering of semitransparent sintered polytetrafluoroethylene films\cite{12}. Yuan researched on Measuring and Modeling the Spectral Bidirectional Reflection Distribution Function of Space Target’s Surface Material\cite{13}; J.E. Hubbs researched on the bidirectional reflectance distribution function of the infrared astronomical satellite solar shield material;\cite{14} Wang researched on Measurement and Modeling of Bidirectional Reflectance Distribution Function (BRDF) on Material Surface\cite{15-16}. Hou carried out BRDF measurement methods for yellow thermal control material, silver thermal control material, solar Panel and coating material\cite{17}.

In this paper, the bidirectional reflectance distribution function of tension polyimide film is measured, which is different from free state film and film plate. In order to characterize the effect of tension on BRDF of thin films, the relative measurement method is used in this paper. The measurement results of free state thin films are taken as reference, and the T-S model and Phong model are used to fit. The best fitting model is given. Bidirectional reflectance distribution function is the ratio of the reflected radiance and the incident irradiance. When the incident light is collimating and the solid angle of the received reflected light is small, the measured value can be used instead of the differential value to calculate the BRDF. The BRDF measured expression is as following\cite{7}:

\[
\text{BRDF} = \frac{dL}{dE} = \frac{L(\theta_r, \phi_r, \lambda)}{L_0(\theta_i, \phi_i, \lambda)} \frac{1}{\Omega \cos \theta_i}
\]

(1)

Where: \(L(\theta_r, \phi_r)\) is the illumination measurement in \((\theta_i, \phi_i)\) direction; \(\Omega\) is the Solid angle of reflected light probe to the center of sample; \(L_0\) is the illumination measurement of the light source. \(L_0\) and \(L(\theta_r, \phi_r)\) are got from Measurement device.

![Figure 1. Incidence and reflected vectors of BRDF model](image)

Because the BRDF measurement of hemispherical space on the sample surface is realized by adjusting the incident angle and reflection angle, it takes a long time to complete the whole hemispherical space measurement process. In order to avoid the problem of large error caused by the long working time and instability of the light source and detector, this paper adopts the comparative measurement method, that is, taking the Yellow polyimide plate as the reference standard plate. The reflectance of yellow polyimide is FB, and the measurement results are obtained when the incident direction is \((0^\circ, 45^\circ)\) and the reflection direction is \((180^\circ, \theta_r)\). The relative measurement formula of BRDF is as follows:
\[
\begin{align*}
\sin \gamma &= \frac{L(\theta, \phi)}{L(0,0)} \\
\gamma &= \frac{1}{\Omega \cos \theta} \\
\Rightarrow f^\circ(\theta, \phi, \theta^I, \phi^I, \gamma) &= \frac{L(\theta, \phi)}{L(0,0)} \\
&= \frac{\cos \theta}{\cos \theta_0} f^b 
\end{align*}
\]  

(2)

2. Measurement device and samples

2.1. Measurement device

According to the measurement model, a BRDF measurement system is built, which includes optical fiber light source, optical fiber spectrum detection, four axis turntable, sample table, control and data processing system. The light source is halogen lamp, which is transmitted to the emitter through optical fiber. The emitter is fixed on the cantilever and emits light to irradiate the center of the sample. The four axis turntable is cantilever turntable and azimuth turntable respectively, which can adjust the incident direction and reflection direction, and the angle measurement accuracy is ± 0.01°. The detector consists of a 2mm diameter optical fiber probe and an optical fiber spectrometer (AvaSpec- NIR256-2.5TEC). The optical fiber probe is fixed on the cantilever of the turntable, aligned with the center of the sample, receives the light in the reflected direction, and measures the reflected light illumination. The spectral resolution of the spectrometer is 0.5nm, and the response spectrum is 300 ~ 750nm. The measurement system is shown in Figure 2. BRDF measurement in hemispherical space of tension film sample can be realized by changing the incident zenith angle $\theta_i$ and reflected zenith angle $\theta_r$ in the incident direction by rotating the cantilever turntable, and changing the incident azimuth $\phi_i$ and reflected azimuth $\phi_r$ by rotating the azimuth turntable, as shown in Figure 2.

![Figure 2 BRDF measurement system](image)

BRDF measurement of sample hemispherical space is realized by changing the incident zenith angle, incident azimuth angle, reflected zenith angle and reflected azimuth angle. In this paper, the incident zenith angle is 5° to 75° with an interval of 5° and the reflected zenith angle is 0° to 90° with an interval of 0.5° to record the data. The azimuths of incidence and reflection range from 0° to 355°. The azimuth adjustment interval is 5 degrees. For each azimuth position, all zenith angles are scanned. The measurement process mainly includes the measurement of the reflection brightness of the standard sample and the tension film sample. The angle adjustment during measuring is as follows: Firstly, to set the zenith angle $\theta_i$ and azimuth angle $\phi_i$ of the incident direction. The azimuth angle $\phi_i$ is set at 180°, and the zenith angle $\theta_i$ is changing from 5° to 75°, and the adjusting step is 5°. Second, to set the zenith angle $\theta_r$ and azimuth angle $\phi_r$ of the light receiver. The azimuth angle $\phi_r$ is changing from the 0° to 355° and the adjusting step is 5°. The zenith angle $\theta_r$ is changing from the 0° to 75° and the adjusting step...
is 5°. Finally, to record the illumination measurement $L'((\theta, \phi))$ of the reflected light in each zenith angles and azimuth angles, and then calculate the BRDF according to the Eq.(2).

2.2. Measured samples
The gold polyimide film with a thickness of 25μm was used as the test sample. In order to achieve different degrees of tension stress, aluminum alloy was used to make a tension ring (Φ30mm * 3mm * 3mm), as the film and tension ring were connected by epoxy adhesive, and the film tension was realized through the thermal expansion of metal. The aluminum alloy tension ring is horizontally placed on the semiconductor heating sheet(TEC1-12705), and connected by thermal conductive silicone grease. The heating temperature of the semiconductor heating plate can be maintained when it is powered on. Through the heating temperature of the metal ring, the expansion of the metal ring is controlled to obtain different degrees of tension stress. After the sample is made, alcohol is used to clean the oil on the film surface, and then the sample is put into the ultrasonic cleaning machine for further cleaning to ensure that there is no residual dirt on the film surface.  The tension ring is heated by semiconductor heating sheet to 20°C, 30°C, 40°C, 50°C. At each temperature point, when the temperature is stable, the surface roughness of the film sample is measured by Taylor roughness meter (Tr20, TIME COMPANY). The test results of equivalent tension and roughness Ra are given following:

| heating temperature /°C | Equivalent tension /N | Ra     |
|-------------------------|-----------------------|--------|
| 20                      | F1=3713               | 0.251  |
| 30                      | F2=4581               | 0.334  |
| 40                      | F3=5362               | 0.386  |
| 50                      | F4=6315               | 0.462  |

![Gold polyimide film](image1)

(a) Gold polyimide film

![Tension polyimide film sample](image2)

(b) Tension polyimide film sample

![Sample on measurement system](image3)

(c) Sample on measurement system

Figure 3 The test sample pictures

![Structure of tension film](image4)

Figure 4 Structure of tension film
3. Measurement result

3.1. Spectral characteristics of BRDF

![Figure 5](image1)

(a) under the F1 tension station  (b) under the F2 tension station

![Figure 6](image2)

(c) under the F3 tension station  (d) under the F4 tension station

Figure 5 $\theta_i = 30^\circ$, BRDF measurement results of sample surface spectrum

Figure 6 $\theta_i = 45^\circ$, BRDF measurement results of sample surface spectrum under the F3 tension station

It can be seen from Figure 5 that the variation trend of BRDF of polyimide surface with wavelength is relatively similar in the range of reflected zenith angle under different tension degrees. In the case of a given wavelength, the BRDF in the specular reflection direction gradually decreases with the increase of the tensile force. This is because with the increase of the tensile force, the polyimide surface is stretched, resulting in the elastic stretching of the molecular chain, which leads to the increase of the roughness, the decrease of the surface reflectance, the enhancement of the light scattering, the decrease of the reflected light intensity in the specular reflection direction, and the decrease of the reflectance with the increase of the tensile force. At the same time, for the fixed incident direction, the BRDF has similar distribution with the increase of reflected zenith angle at different wavelengths, but the BRDF value increases linearly with the increase of wavelength. The longer the wavelength is, the larger the
BRDF value is. It can be seen that the BRDF of polyimide film has spectral distribution characteristics. This characteristic is verified from Figure 6. With the change of the zenith angle, the law of BRDF changing with the wavelength does not change, and reaches the maximum value near the specular reflection direction.

3.2. Spatial characteristics of BRDF

Figure 7 $\lambda = 650$ nm, Measurement results of BRDF curve with reflected zenith angle under the F1 tension station

![BRDF curve with reflected zenith angle](image)

Figure 8 $\lambda = 750$ nm, Measurement results of BRDF curve with reflected zenith angle under the F1 tension station

It can be seen from Figure 7 that BRDF increases first and then decreases with the increase of the reflected zenith angle, and the change curve is relatively gentle, reaching the maximum value near the specular reflection direction in the incident direction, and BRDF values are distributed in the range of ±10° near the specular reflection direction. When $\theta_i = 15°$ and $\theta_i = 55°$, the variation trend of BRDF with reflected zenith angle is similar to that of $\theta_i = 30°$. The results show that the variation trend of BRDF with the reflected zenith angle is independent of the incident zenith angle, and there is a maximum value in the mirror direction. With the reflected zenith angle increasing first and then decreasing, the distribution of BRDF with the mirror direction is Gaussian. When the incident zenith angle $\theta_i < 45°$, the variation curve of BRDF with the reflected zenith angle is relatively slow, and the BRDF value is relatively small. When $\theta_i > 45°$, the variation curve of BRDF is relatively steep. The main reason for this phenomenon is the effect of angle factor $\cos \theta$. It can be seen from equation 1 that there is a cosine term of the reflected zenith angle $\theta_r$ in the BRDF absolute measurement model. With the increase of $\theta_r$, the angle factor first increases and then gradually decreases, resulting in the BRDF first increases and then decreases. The variation trend of BRDF is verified again from Figure 8. For the samples with...
different tension, BRDF increases first and then decreases with the increase of reflected zenith angle, reaching the maximum value near the specular reflection. BRDF values are distributed in the range of $\pm 5^\circ$ near the specular reflection direction, showing a Gaussian distribution. It can be seen that there is spatial distribution of BRDF in tension polyimide film.

3.3. Variation of BRDF with roughness

The measurement results of the same wavelength under different incident zenith angles and different roughness are shown in Fig.9 and Fig.10.

Figure 9 $\lambda=650\text{nm}$, $\theta_i=30^\circ$, Curve of BRDF changing with reflected zenith angle

Figure 10 $\lambda=650\text{nm}$, $\theta_i=45^\circ$, Curve of BRDF changing with reflected zenith angle

It can be seen from Figure 9 that the surface roughness of the sample has a certain influence on the spatial distribution of BRDF. Combined with table 1, with the increase of polyimide tension, the roughness increases, and the intensity slightly deviating from the specular reflection direction increases. The maximum value is near the specular reflection direction. The BRDF changes with the reflected zenith angle in a Gaussian distribution. With the decrease of the roughness, the BRDF curve transits from an approximate hyperbola to a Gaussian curve. It can also be shown from Figure 10 that with the increase of roughness, the reflection intensity of scattering in all directions gradually increases, and the reflection intensity near the specular reflection direction gradually decreases. With the increase of the incident zenith angle, the shielding effect caused by the surface roughness is gradually obvious, the reflection intensity of the sample in the specular reflection direction decreases, and the scattering in all directions is gradually strengthened.
3.4. BRDF measurement fitting

BRDF models commonly used at this stage, such as Phong model, Torrance sparrow model (T-S model), etc. T-S model assumes that the surface of an object is composed of a large number of smooth micro planes with random orientation, and these micro plane elements are perfect reflection surfaces. Phong model assumes anisotropy, considering the specular reflection and diffuse reflection of the surface, fitting the BRDF results of the different tension station with incident 30° angles.

Comparing the two fitting results, it can be seen that the BRDF of polyimide surface changes slowly with the reflected zenith angle, and the Phong fitting results are in good agreement with the distribution trend of measured values near the specular reflection direction. At the angle far away from the mirror reflection direction, T-S fitting results are better. When the reflection zenith angle is less than 45 degrees, the BRDF curve is relatively flat, T-S fitting is good, and the similarity reaches 0.948; when the reflection zenith angle is more than 45 degrees, the BRDF curve is relatively steep, and Phong fitting is good, reaching 0.919. It can be seen that the polyimide surface BRDF needs to integrate a variety of models to obtain a better fit.

4. Conclusion

In this paper, the BRDF measurement is used to measure the bidirectional reflectance distribution function of tensile film. The light spectrum is from 200nm to 1170nm. Taking tension polyimide film as an example, BRDF was measured, and the measurement results were fitted by T-S model and Phong model, and the fitting accuracy was compared. The measurement results show that the BRDF of
polyimide plane are different with the tensile stress, and the reflectance intensity in the reflective direction decreases with the increase of the tensile stress, increases with the wavelength of the incident light. The reflectance intensity is associated with the roughness changing of polyimide surfaces for the tensile stress, as the roughness increases with the more stress, and the intensity increases in the none reflective direction. The fitting precision is more than 95% with the T-S model according to the classical Phong model. The research data can be used to evaluate the reflective intensity of pharmaceutical packaging film, medical light barrier film, thermal insulation film and other film materials.

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References
[1] NICODEMUSF E. Directional reflectance and emissivity of an opaque surface[J]. Applied Optics, 1965, 4(7):767775.
[2] Torrance K E, Sparrow E M. Theory for off-specular reflection from roughened surfaces[J]. Journal of the Optical Society of America, 1967, 57(9): 1105-1112
[3] marschne R S R, westin SH, lafo R T et al, Image-based bidirectional reflectance distribution function measurement[J]. Applied Optics. 2000, 39(16):2592600
[4] Chris Wynn. An Introduction to BRDF-Based Lighting[J]. NVIDIA Corporation 2000.
[5] PRIEST R G, MEIER S R. Polarimetric microfacet scattering theory with applications to absorptive and reflective surfaces[J]. Optical Engineering, 2002, 41(5):988-993.
[6] T. W. Stuhlinger, E. L. Dereniak, F. O. Bartell, Bidirectional reflectance distribution function of goldplated sandpaper[J] Appl. Opt. , 1981, 20(15): 2648~2655
[7] liu chenhao, li zhi, xu can, a modified phong model for frusnel reflection phenomenon of commonly used materials for space targets[J], laser & optics progress, 54 ,2017,102901
[8] yuan yan, sun chengming, zhang xiubao, measuring and modeling the spectral bidirection reflection distribution function of space target's surface material[J],acta physica sinicina, 2010,59(3),2097~2103
[9] Fontanot T, Audenaert J,Hanselaer P,TBRDF characterization of Al-coated thermoplastic polymer surfaces[J],Journal Of Coatings Technology And Research,Jun 2020,17(5):1195-1205
[10] Yang PY; Zhang, ZM M,Bidirectional reflection of semitransparent polytetrafluoroethylene (PTFE) sheets on a silver film[J],international journal of heat and mass transfer,FEB 2020,148
[11] Prater, W, Tran, N, McGarvey, S,surface scanning inspection system particle detection dependence on aluminum film morphology[J],Conference on Metrology, Inspection, and Process Control for Microlithography XXVI,SPIE,2012,8324
[12] Li, Q,Lee, BJ,Zhang, ZM,Allen, DW,Light scattering of semitransparent sintered polytetrafluoroethylene films[J], journal of biomedical optics,2008,13(5)
[13] Yang Fan , Xuan Yimin, Han Yuge , Infrared characteristics of spacecraft undulating surface[J],Infrared and Laser Engineering,Vol.45 No.5,May 2016,0504003
[14] J.E. Hubbs, L.D.Brooks, M.J. Notzigeret al., Bidirectional reflectance distribution function of the infrared astronomical satellite solarshield material[J].Appl.Opt.,1982, 21(18) : 3323~3325
[15] Wang Hongyuan, Zhang Wei. Infrared characteristics of onorbit targets based on space-based optical observation [J].Optics Communications, 2013, 290: 69-75.
[16] Wang H, Zhang W, Dong A. Measurement and Modeling of Bidirectional Reflectance Distribution Function (Brdf) on Material Surface[J]. Measurement: Journal of the International Measurement Confederation. 2013,46(9):3654~3661
[17] Hou Q, Wang Z, Su J, et al. Measurement of Equivalent Brdf on the Surface of Solar Panel with Periodic Structure[J]. Coatings. 2019,9(3):193