Mechanical analysis of lateral uplift of aluminum film scribed by grating

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Abstract. During the diffraction grating scoring process, the stress change on the aluminum film greatly affects the groove morphology. In view of the current status of "trial and error" of grating scoring, in order to study the rule of lateral bulging of aluminum film in the process of grating scoring, this paper aims at the formation rule of groove topography during the process of grating scoring, which is affected by the change of the surface film material force. The slip line field theory and the speed upper limit field theory establish a simple model for the stress process of the material during the scoring process.

1. Introduction

The current diffraction grating scoring technology mainly adopts the "trial and error" method to determine the grating parameters, which not only wastes time but also increases costs, and it is difficult to say that it is scientific and effective. At the same time, there is a certain chance. Existing experience is not suitable for the grating scoring tasks with new parameters. The fundamental reason is that there is no deep understanding of the formation mechanism of the groove during the grating scoring process. And according to previous studies, the change of the stress on the aluminum film during the scoring process has a great influence on the change of the groove shape. Therefore, according to the mechanical scoring technology, the mechanical analysis of the grating scoring process can be used to realize the recognition of the groove formation process in the mechanical scoring process and the influence of the material flow law on the groove morphology and mechanical characteristics law, so as to lay a solid foundation for grating scoring technology.

2. Mechanical analysis of uplift

Figure 1 is a schematic diagram of the groove cross section at a certain moment in the scoring process. The volume of the removed material is the $G_1$ area, and its volume is equivalent to $2G_2$ material attached to the surface as a build-up material, forming a lateral bulge. For pure plow cutting, there is no material removal, only the material is moved to both sides. If the springback phenomenon at the bottom of the groove is not considered, $G_1=2G_2$.

However, the grating scoring process is a complex three-dimensional process. Due to the inherent geometric complexity of plastic mechanics analysis, it is difficult to establish a mechanical analysis model that can simultaneously satisfy the equilibrium equation, the coordination equation and the plastic flow criterion. However, by considering that material flow occurs on the flow chip plane, the above problem can be simplified into a two-dimensional model. The material flow plane connects the front end of the tool and both sides.
The flow pattern of materials with different depths on the chip flow plane is shown in Figure 1(b). For the upper part, the flow chip plane is A-A, and the material flow pattern can be determined by the model of slip line field. The slip line field established on the chip flow plane is shown in Fig. 1(a). The material passes through the slip line B-P into the flow chip plane and flows out of the plane through the slip line G-R. Since the shape of the entrance cannot be known, the entrance is regarded as a single tangent line, as shown in Figure 1(b). The exit is regarded as a smooth transition plane. If it is only regarded as a single tangent line, the pressure of the vertices GRE will be too large, and the slip line field theory will no longer be applicable.

As the movement continues downward, and considering the flow phenomenon occurring in the C-C plane, there is not enough space to establish a slip line field. Therefore, the inlet and outlet of the material can be regarded as parallel tangents, and the upper limit method is used to solve the problem of material flow. Connect these tangents to get a shear plane. The upper surface of the upper limit model is a parallelogram, and the side gradually decreases toward the chip flow plane H-H, which connects the apex of the tool and the publicly constructed upper surface. The proposed plough cutting model is a combination of slip line field model and upper limit model.

When calculating the force, the force on the effective plane is calculated first, and then the force on the contact surface between the tool and the material is calculated according to the force on the effective plane. When using the slip line field model, the mechanical model on the contact surface can be solved by the stress generated by the free surface on the ridge. When applying the upper boundary field model, the energy consumed by the cutter surface and the shear plane is first calculated to solve the stress problem of the cutter.

The cutting force is the force on the effective plane. When it is in the range of 0-z, the upper field model is used; in the range of z-h, the slip line field model is used.

2.1. Mechanical analysis in the slip line field
Figure 2. Material flow plane stress

As shown in Figure 2, $\sigma_i$ is the normal stress on BP. Considering the differential $d\omega$ of the tool depth in the effective plane, the force on BP is

$$f_x = [\sigma_i \cos \varphi - k \frac{\sin \varphi}{\cos(90-\eta_c)}] \frac{t}{\sin \psi} d\omega$$ (1)

$$f_y = [\sigma_i \sin \varphi + k \frac{\cos \varphi}{\cos(90-\eta_c)}] \frac{t}{\sin \psi} d\omega$$ (2)

Where $k$ is the yield stress during cutting. The power on GE is

$$f_{ox} = k[1 - \frac{1}{\sin(\eta_c - 2\theta_e)}] t d\omega$$ (3)

$$f_{oy} = k[1 + \frac{1}{\sin(\eta_c - 2\theta_e)}] t d\omega$$ (4)

Therefore, the positive pressure and shear force on the tool surface are

$$f_n = (f_{iy} + f_{oy}) \cos \alpha_e - (f_{ix} + f_{ox}) \sin \alpha_e$$ (5)

$$f_t = (f_{iy} + f_{oy}) \sin \alpha_e - (f_{ix} + f_{ox}) \cos \alpha_e$$ (6)

The resultant force can be obtained by the above equation, simplify the above formula, eliminate the parameters $t$ and $d\omega$ on the tool surface, other factors remain unchanged, and the geometric relationship of the tool can be known as

$$t = \frac{h-z}{\sin \eta_c} = \omega \frac{\cos(\theta+\beta)}{\sin \eta_c} \frac{1}{\sin \psi}$$ (7)

Where $\omega$ is the limit height value of the effective plane obtained by measurement. At any point on $z$, the force on the tool surface can be calculated by the slip line field model, which can be obtained

$$AT = \int_0^\omega \frac{\sin \eta_c}{2 \cos(\theta+\beta)} \frac{(h-z)^2}{\sin \psi}$$ (8)

Which

$$\omega = (h - z) \frac{\sin \eta_c}{\cos(\theta+\beta)}$$ (9)

The positive pressure and shear force on the tool surface are
The dimensionless quantity of the force on the tool surface is

\[ F_{nn} = \frac{F_n}{kh^2} \quad (12) \]

\[ F_{tt} = \frac{F_t}{kh^2} \quad (13) \]

The friction coefficient of the tool surface has a certain functional relationship with the above two forces. If the friction coefficient is \( \mu \), then there is

\[ F_{tt} = \mu F_{nn} \quad (14) \]

Therefore, \( F_{tt} \) and \( F_{nn} \) are available. The components of the two forces on the x, y, and z axes are shown in Figure 3. Therefore, the component forces of \( F_{tt} \) and \( F_{nn} \) on the x, y, and z axes are:

\[ F_{tx} = F_{tt} \cos \beta_1 \sin \beta_2 + F_{nn} \cos \beta_3 \sin \beta_4 \]

\[ F_{ty} = -F_{tt} \cos \gamma \cos \alpha_e + F_{nn} \cos \gamma \sin \alpha_e \]

\[ F_{tz} = -F_{tt} \sin \beta_3 + F_{nn} \sin \beta_3 \]

According to the geometric relationship of the tool, the above formula can be simplified as

\[ F_{tx} = F_{tt} \sin \alpha_e + F_{nn} \cos \alpha_e \]

\[ F_{ty} = -F_{tt} \cos \gamma \cos \alpha_e + F_{nn} \cos \gamma \sin \alpha_e \]

\[ F_{tz} = -F_{tt} \sin \gamma + F_{nn} \sin \gamma \]

2.2. Mechanical analysis in the upper field

When the tool surface ABGA is plastically deformed by the friction generating surfaces ABPHA and AGRHA, energy is lost. Let ABPHA, AGRHA, and ABGA areas be \( A_1 \), \( A_2 \), and \( A_3 \), respectively. The total energy consumption is

\[ W_T = kV_d A_1 + kV_d A_2 + \tau_f V_c A_3 \]

The component force in the direction of tool movement is

\[ F_{hx} = \frac{W_T}{v} \]
Set the positive pressure and shear force on the cutter surface to be $F_{bp}$ and $F_{bt}$, respectively, from the geometric relationship in Figure 3, we can get:

$$F_{bx} = F_{bp} \cos \alpha_2 \sin \alpha_1 + F_{bt} \sin \alpha_e$$  \hspace{1cm} (21)
$$F_{by} = F_{bp} \cos \alpha_2 \cos \alpha_1 - F_{bt} \cos \gamma \cos \alpha_e$$  \hspace{1cm} (22)
$$F_{bz} = -F_{bp} \sin \alpha_2 - F_{bt} \sin \gamma \cos \alpha_e$$  \hspace{1cm} (23)

According to the geometric relationship of the tool and the surface friction coefficient, we can get:

$$F_{bt} = \mu F_{bp}$$  \hspace{1cm} (24)

$F_{bp}$ can be derived from formula (21), $F_{bp}$ acts on the $A_3$ surface, therefore, the normal stress on the $A_3$ surface

$$\sigma_f = \frac{F_{bp}}{A_3}$$  \hspace{1cm} (25)

Using the relationship $\tau_f = \mu \sigma_f$, the stress on the blade surface can be obtained:

$$\frac{\sigma_f}{\kappa} = \frac{\mu (A_1 + A_2)}{A_3 [\nu (\cos \alpha_2 \sin \alpha_1 + \mu \sin \alpha_2) - \mu \nu_c]}$$  \hspace{1cm} (26)

The magnitude of normal stress can be obtained.

3. Conclusion

In this paper, the influence of the groove formation process and material flow law on the groove shape and mechanical characteristics during mechanical scribing is explored. The complex three-dimensional scribing process is reduced to a simple two-dimensional model. The concept of the flow plane, based on the theory of the slip line field and the upper limit method, analyzes and solves the stress process of the material during the grating scoring process.

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