Thermal shock resistance of ZnS wave-transparent ceramic considering the effects of constraint and pneumatic pressure

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In order to study the combined effect of aerodynamic heating, pneumatic pressure and external constraint on the thermal shock resistance (TSR) of ZnS wave-transparent ceramic in its actual service process, the theoretical model is established by introducing the analytical solution of transient heat conduction problem of ZnS plate under aerodynamic heating into its thermal stress field model. The numerical simulation is also conducted not only to examine the theoretical model, but also to study how to improve the TSR. The influences of constraint and pneumatic pressure are studied and the effects of loosening constraint and active cooling are focused on. The study shows that the critical rupture temperature difference of simply supported ZnS plate will form wave peak; the TSR of ZnS plate is obviously optimized when loosening constraint method has been adopted, and the effect of pneumatic pressure on TSR is closely related to the change of failure region; active cooling is an effective way to improve the TSR of ZnS plate and the stronger pneumatic pressure, the better TSR, but active cooling can’t be too violent.

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1. Introduction

As a kind of multifunctional material which protect communication, telemetry, guidance and other systems of near space vehicle, wave-transparent material is widely used in radio systems of launch vehicles, high-speed missiles, flying wings, unmanned aerial vehicles and other aircraft. The wave-transparent ceramic material can also be divided into two major categories of wave-transparent polymer material and wave-transparent ceramic material by its composition. The wave-transparent ceramic material has the advantage of high melting point, ablation resistance and stable performance when compared with the other, so it’s attracting more and more attention currently.

ZnS wave-transparent ceramic has been developed since 1960s as a kind of antenna window material. As it has the characteristics of high melting point, high IR transmittance (0.4–14 μm), good mechanical and thermal properties, atmospheric corrosion resistance and low manufacturing cost, ZnS wave-transparent ceramic is widely used in long-wave infrared antenna window. The research of it mainly focused on the phase structure and preparation of ZnS powder, or the hot-pressing technique and related post-processing of ZnS ceramic. In addition, the mechanical and optical properties of ZnS wave-transparent ceramic were also extensively studied.

With the increase of speed, the severe service environment of near space vehicle gives a harsh demand for the thermal shock resistance (TSR) of ZnS antenna window under the mechanical/heat coupling conditions. But the TSR of ceramic is really poor due to its inherent brittleness. Therefore, improving the TSR of ceramic has been one of the most important focal points in the ceramic field. The second TSR parameter $R'$ was used by Harris to study the TSR of ZnS wave-transparent ceramic, but the application environment and applicable conditions of $R'$ were neglected.

In order to study the typical situation (when used as antenna window of near space vehicle, ZnS wave-transparent ceramic is subjected to aerodynamic heating, pneumatic pressure and external constraint in its service process), the external constraint and pneumatic pressure are considered and the heat transfer condition and critical rupture temperature difference are used to characterize the TSR of ZnS plate in this paper. The improvements of the TSR of ZnS plate by using the methods of loosening constraint and active cooling are compared, so as to give effective suggestions and provide both theoretical basis and technical guidance for the design and application.

2. Theoretical model

The geometric model is shown in Fig. 1: A thin rectangular ceramic plate is considered with the $x$-$y$ plane as its middle plane and $z$ as the thickness coordinate. The length, width and thickness of the thin plate which is simply supported on four sides is $a$, $b$ and $h$ respectively. Its upper surface is imposed with surface heat flux $q$, and pneumatic pressure $P$ ( $P$ is assumed to be uniform load and perpendicular to the middle plane) at $t = 0$, and the lower surface is insulated (when active cooling is adopt, the lower surface is subjected to convective cooling).

Assumptions that have been adopted are given below:

1. The establishment of model follows the Kirchhoff hypothesis and the body force is ignored.
2. The plate is continuous, homogenous, isotropic, elastic and submits to small deformation hypothesis.

3. The thickness of the plate is very small in relation to the transverse dimensions (according to the classical thin plate theory: \(1/80<h/b<1/5\))\(^{25}\), and under this condition, the conduction is assumed to occur in the \(z\)-direction only.\(^{26}\)

Generally speaking, once the thermal stress caused by the temperature gradient is greater than the fracture strength of the ceramic, cracks will be generated and result in instant fracture.\(^{18,20}\) Besides, the maximum stress appears at the surface for the most cases, so it’s reasonable to regard that the plate fails when the thermal stress of the surface caused by thermal shock is equal to or greater than the fracture strength of material.

### 2.1 Pneumatic pressure

Deflection \(w\) is usually assumed as unknown function while all other physical quantities are expressed by it when dealing with thin plate under small deflection. ZnS antenna window is constrained on four sides in its actual service process, so the typical situation (simply supported on four sides) is studied. The boundary condition can be satisfied when deflection \(w\) is expressed as double trigonometric series:

\[
w = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} A_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}
\]

where \(A_{mn}\) is undetermined coefficient.

Introducing the expression of deflection \(w\) into the differential equation of plate bending,\(^{25}\) \(A_{mn}\) and \(w\) can be obtained and expressed as:

\[
A_{mn} = \frac{16\rho}{\pi^6 D m a^2 + n^2 b^2}
\]

\[
w = \frac{16\rho}{\pi^6 D} \sum_{m=1,3,5,\ldots}^{\infty} \sum_{n=1,3,5,\ldots}^{\infty} \frac{m\pi x}{a} \sin \frac{n\pi y}{b}
\]

where \(D\) is the bending rigidity of the plate\(^{25}\) and \(\rho\) is pneumatic pressure.

So the corresponding stress components can be calculated using Eqs. (3) and (4):

\[
\sigma_x = -\frac{Ez}{1-v^2} \left(\frac{\partial^2 w}{\partial x^2} + \frac{v}{1-v} \frac{\partial^2 w}{\partial y^2}\right)
\]

\[
\sigma_y = -\frac{Ez}{1-v^2} \left(\frac{\partial^2 w}{\partial y^2} + \frac{v}{1-v} \frac{\partial^2 w}{\partial x^2}\right)
\]

where \(E\) and \(v\) are Young’s modulus and Poisson’s ratio respectively.

### 2.2 Thermal stress

#### 2.2.1 Thermal stress field model

When considering thermal stress, the equilibrium differential equation of plate can be expressed as (static problem, ignore the dynamic term):

\[
D \frac{\partial^4 w}{\partial x^4} = \frac{M_T}{1-v} \left( M_T = \alpha E \int_{-h/2}^{h/2} (T(z, t) - T_i) \, dz \right)
\]

where \(D\) is the bending rigidity of the plate, \(M_T\) is bending moment caused by thermal stress, \(\alpha\) is the thermal expansion coefficient, \(T_i\) is initial temperature (the uniform temperature of the plate prior to being subjected to thermal shock) and \(T(z, t)\) is current temperature (the temperature model in 2.2.2 will be adopted).

When considering the boundary condition, \(M_T\) and \(w\) are expressed as double trigonometric series, so finally the expression of \(w\) can be obtained:

\[
w(x, y) = \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} B_{mn} \frac{1}{(1-v)\pi^2 D} \left( \frac{m^2 x^2}{a^2} + \frac{n^2 y^2}{b^2} \right) \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}
\]

Combining the Eq. (6) and physical equations, the stress field of plate can be expressed as:

\[
\sigma_x = -\frac{Ez}{1-v^2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{m^2 \pi^2 C_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}}{a^2 + b^2} \\
- \frac{E\alpha}{1-v} \left( T(z, t) - T_i \right)
\]

\[
\sigma_y = -\frac{Ez}{1-v^2} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{n^2 \pi^2 C_{mn} \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b}}{a^2 + b^2} \\
- \frac{E\alpha}{1-v} \left( T(z, t) - T_i \right)
\]

\[
\tau_{xy} = -\frac{Ez}{1-v} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \frac{m n \pi^2 C_{mn} \cos \frac{m\pi x}{a} \cos \frac{n\pi y}{b}}{a b} \\
- \frac{E\alpha}{1-v} \left( T(z, t) - T_i \right)
\]

where \(C_{mn}\) and \(B_{mn}\) are undetermined coefficients, which can be expressed as:

\[
C_{mn} = \frac{B_{mn}}{(1-v)\pi^2 D} \left( \frac{m^2}{a^2} + \frac{n^2}{b^2} \right)
\]

\[
B_{mn} = \frac{4}{a b} \int_{-h/2}^{h/2} M_T \sin \frac{m\pi x}{a} \sin \frac{n\pi y}{b} \, dx \, dy
\]

\[
= \frac{4 M_T}{\pi^2 m n} (1 - \cos \frac{m\pi}{a}) (1 - \cos \frac{n\pi}{b})
\]
2.2.2 Transient temperature field model

When considering a thin plate which is initially at a uniform temperature \( T_i \) and imposed with constant surface heat flux \( q_s \) at its upper surface, the transient temperature field of it can be obtained by solving the differential equation and definite conditions of this problem, and the result is as follows:24,26

\[
T(\xi, t) = T_i + \frac{h q_s}{k} \left[ \frac{a t}{\pi^2 n^2} \left( 1 - \exp\left( -\frac{n^2 \pi^2 t}{a} \right) \right) \cos \left( \frac{n \pi}{2} \left( \frac{h}{2} + 2 \right) \right) \right]
\]

(9)

where \( a \) is thermal diffusivity (\( a = k / \rho c \)), where \( \rho, c \) and \( k \) are density, specific heat and thermal conductivity respectively.

Before the temperature of the insulated lower surface being changed, the model of the semi-infinite solid can also be used for the transient temperature field of the plate. The analytical solution of the semi-infinite solid, which is initially at a uniform temperature \( T_i \) and imposed with constant surface heat flux \( q_s \) at its upper surface, is obtained in:26

\[
T(\xi, t) = T_i + \frac{2 q_s}{k} \sqrt{\frac{a t}{\pi}} \exp\left( -\frac{\xi^2}{4 a t} \right) - \frac{q_s \xi^2}{k} \text{erfc}\left( \frac{\xi}{2 \sqrt{a t}} \right)
\]

(10)

\[
\text{erfc} \, \omega \equiv 1 - \text{erfc} \, \omega \equiv 1 - \frac{2}{\sqrt{\pi}} \int_0^\infty \exp(-x^2)dx \]  

(10)

where \( \xi \) is the distance to the upper surface, and \( \text{erfc} \) is the complementary error function.

As the Eq. (10) doesn’t need to calculate the infinite series and further verify its convergence, it’s relatively convenient for calculation when compared with Eq. (9). In this paper, according to the specific thermal shock process, the Eq. (10) is adopted before the temperature of the lower surface being changed, while the Eq. (9) is adopted for the long time thermal shock situation of which the lower surface temperature has already been changed, so as to insure both accuracy and efficiency.

2.3 Combined effect

Suppose there is no interaction between aerodynamic heating and pneumatic pressure, so the linear superposition of their effects can be used to study the TSR of ZnS plate under the premise of small deformation.

2.4 Characterization of the TSR

It’s frequent to use some parameters to character the TSR of ceramics, especially the first TSR parameter \( R \) and the second TSR parameter \( R' \).18,19,23,28

The first TSR parameter \( R \) describes an extreme situation: the ceramic plate is heated up or cooled down rapidly, so the surface is subjected to a sudden temperature change \( \Delta T (\Delta T = T_{surf} - T_i) \) while the inside temperature is held to be constant.18,19,23,28

Due to the temperature gradient in the thickness direction, the transient thermal stresses generated. The maximum stress occurs on the surface \( R \) and may be large enough to reach the fracture strength:

\[
\sigma_{max} = \sigma_{surf} = - \frac{E \alpha \Delta T}{1 - \nu}
\]

(11)

When \( \sigma_{max} \) reaches the fracture strength \( \sigma_{fr} \), the critical rupture temperature difference \( \Delta T_{cr} \) (maximum allowable temperature difference) and the first TSR parameter \( R \) can be obtained as:

\[
R = \Delta T_{cr} = abs(T_{surf} - T_i) = \sigma_{fr} \frac{1 - \nu}{E \alpha}
\]

(12)

where the temperature at which the material fails is the critical rupture temperature \( T_{cr} \), and the difference between \( T_c \) and \( T_i \) (thermal shock initial temperature) is the critical rupture temperature difference \( \Delta T_c \). Obviously, as an ideal case, \( R \) is the lower limit of the critical rupture temperature difference of the plate in different thermal shock situations.

The parameter \( R \) only reflects the relationship between the mechanical properties and the TSR, so in order to obtain the more accurate analytical solution, the second TSR parameter \( R' \) is defined as follows:18,19,23,28

\[
R' = \frac{\sigma_{fr}}{E \alpha} \left( 1 - \nu \right) k
\]

(13)

So the second TSR parameter \( R' \) can reflect both mechanical properties and the thermal conductivity of materials. Generally, the critical rupture temperature difference is expressed as:18,19,20,29

\[
\Delta T_{cr} = \frac{R'}{0.33 h_t}
\]

(14)

where \( h \) is the thickness of ceramic plate, \( t_i \) is the surface heat transfer coefficient.

Many studies suggest that the greater the \( R' \), the more difficult it is to initiate cracking and the better the TSR is.19,20,29 But \( R' \) isn’t applicable to all thermal shock situations,23,27 so the heat transfer condition (product of surface heat flux and plate thickness) is defined and used together with critical rupture temperature difference to characterize the TSR of ceramics.23,24

3. Numerical simulation

The numerical simulation is accomplished by using the software SIMULIA Abaqus 6.10–1. According to the symmetry of the model, one-fourth of the plate is used in the numerical simulation, as shown in Fig. 2(a). The left and lower sides are restricted by applying the symmetric constraint and the right and upper sides are simply-supported.

The sequentially coupled thermal stress analysis is used for calculation. The first-order elements (8-node convection-diffusion brick elements: DCC3D8) are used in the transient heat transfer analysis in order to lump the heat capacity terms and avoid oscillation while the second-order elements (20-node quadratic brick, reduced integration elements: C3D20R) are used in the thermal stress analysis in order to provide the first-order thermal strain field, which is consistent with the first-order temperature field provided by the first-order temperature elements.

The material parameters of ZnS are shown in Table 1. Because of the large stress and temperature gradients due to the thermal shock on upper surface, the local mesh refinement is used in the region from upper surface to one-eighth thickness, as shown in Fig. 2(a). The common size of antenna window (200*200*16 mm, typical thin plate structure) is adopted in the calculation (100*100*16 mm is used in the numerical simulation). Known from the symmetry of the model and the properties of sine function used in the expressions of \( w \), the extreme values of stress and deflection should be obtained at the midpoint of upper surface or lower surface, so as shown in Table 2, the stresses and temperatures at the midpoint of upper surface corresponding to different mesh densities are calculated (\( t = 1 \text{s}, T_i = 200 \text{C}, q_s = 1 \text{MW/m}^2 \)), so as to compare the convergence of different element sizes: 20 mm (thickness: 0.5 mm); 10 (0.25); 5 (0.125);
2.5 (0.0625). The ratio of thickness $h$ to transverse dimension $b$ is fixed ($1/40$, which meets the requirement of classical thin plate theory) in the mesh refinement region. Synthesize all the results, the element size 5 mm (as shown in Fig. 2(a), the numbers of elements on the length, width and mesh refinement region in the thickness direction are 20, 20 and 16 respectively) is used to insure both accuracy and efficiency. In the following calculations, the plate size remains unchanged and the initial temperature is changed only in the situation of Fig. 9.

As shown in Figs. 2(b) and 2(c), the influences of loosing constraint and active cooling on the TSR of ZnS plate are studied. In order to loose the constraint on four sides, the elastic material of which the thickness is 10mm is supposed to be well-bonded around the ZnS plate (the elastic material will use the material parameters of ZnS on trial firstly, and the elastic modulus is adjustable), and the four sides of the elastic material are still simply supported, as shown in Fig. 2(b). The element size is the same as situation (a). As shown in Fig. 2(c), when the lower surface of ZnS plate is assumed to be imposed with active cooling, local mesh refinement is also needed in the region from lower surface to one-eighth thickness because of the large stress and temperature gradients, and the element size is also the same.

### 4. Results and discussion

Due to lack of the data of compressive strength, ZnS is assumed to be tension and compression isotropic for simplicity (the prediction is conservative for the compressive failure cases). The values of critical rupture temperature difference in this paper are all taken from the upper surface which is imposed with heat flux. The ZnS plate fails when the normal stress of the midpoint of upper surface or lower surface is equal to or greater than it’s fracture strength. In addition, the positive value is tensile stress and the negative value is compressive stress in the calculation.

First of all, the convergence of theoretical results is verified, as shown in Table 3. The midpoint of upper surface is taken as the calculating point ($t = 0.2$ s, $p = 5 \times 10^5$ Pa, $q_s = 1$ MW/m$^2$). Synthesize all the results, in order to meet the accuracy requirements, the values of $m$, $n$ from Eqs. (3) and (7) are 99 respectively.

The temperature fields of simply supported ZnS plate at different times are calculated and shown in Fig. 3. The theoretical results agree well with numerical ones, so it’s reasonable to use Eq. (10) in the calculation.
Tensile failure occurs at the midpoint of the upper surface in Fig. 4. The results clearly reflect that as the increase of heat transfer condition, the critical rupture temperature difference of simply supported ZnS plate (when $p = 0$ Pa) will form wave peak.

When the heat transfer condition is relatively small (thermal shock isn’t violent), the maximum stress caused by temperature gradient in the thickness direction can’t result in the rupture of the upper surface, and as the time increases, the temperature gradient tends to be stable. But due to the existence of constraint, the temperature and deformation of the plate increase gradually and finally result in the rupture as the thermal shock time increases. When the heat transfer condition is large (violent thermal shock), the stress caused by the temperature gradient in the thickness direction is large enough to cause the thermal shock failure of the upper surface. So the correlation curve is the result of the combined action of two failure mechanisms.

Figure 4 shows that when the heat transfer condition is relatively small (constraint is the main influence factor), the TSR will form wave peak; when the heat transfer condition is large (stress caused by temperature gradient is the main influence factor), the TSR is poor and not sensitive to the change of it.

In Fig. 5, when the upper surface of the simply supported plate is imposed with pneumatic pressure, the compressive stress will generate on the upper surface and the tensile stress on the lower surface; when imposed with surface heat flux, the plate bulges upwards to satisfy the requirement of deformation conditions, and the stress distribution is: upper surface (strong tensile stress), near the middle layer (compressive stress), lower surface (weak tensile stress). So the combined action results in stress relaxation on upper surface and the intensification of stress on lower surface, and damage may firstly occur at the midpoint of the upper surface or the lower surface. As it can be seen in Fig. 5, failure region changes at the critical point.

Combined with stress analysis above, the conclusions can be obtained from Fig. 5: if failure occurs on upper surface, the strong pneumatic pressure corresponds to the better TSR under the same heat transfer condition; if failure occurs on lower surface, the situation is opposite: the stronger pneumatic pressure, the poorer TSR. Certainly, the plate will rupture rapidly if the pneumatic pressure is too strong. So the poor TSR situation needs to be avoided in the actual service according to conclusions above.

The effect of loosing constraint on the TSR is studied in Figs. 6 and 7. As it can be seen in Fig. 6:
1. The TSR of ZnS plate is obviously optimized when loosing constraint method has been adopted: free boundary condition case and simply supported boundary condition case are the upper limit and lower limit of the critical rupture temperature difference respectively.
2. The TSR of ZnS plate is negatively correlated with the Young’s modulus, and it’s sensitive to the change of Young’s modulus when Young’s modulus is small.
As it can be seen in Fig. 7:

3. When the Young’s modulus is relatively small, there is a critical value of the heat transfer condition. If the heat transfer condition applied on the plate is smaller than this critical value, thermal shock won’t result in the failure until its melting point.25 That is to say, when the heat transfer condition is very small, the failure caused by the temperature gradient in the thickness direction can’t result in rupture, and even as the time increases, the increasing deformation is relaxed by the soft elastic material around the plate. If the Young’s modulus is too large, the similar situation as Fig. 4 will occur.

In Fig. 8, the similar situation as Fig. 5 occurs when pneumatic pressure and surface heat flux are applied: stress relaxation on upper surface and the intensification of stress on lower surface.

As it can be seen in Fig. 8:

1. The TSR of the plate could be effectively improved (compared with Fig. 5) if loosing constraint method had been adopted in the actual service.

2. When pneumatic pressure is relatively small, the failure region (upper surface) keeps unchanged, the strong aerodynamic thermal environment should be avoided in the service as the TSR is negatively correlated with the heat transfer condition.

3. The critical rupture temperature difference will form wave trough (a danger heat transfer condition range) when pneumatic pressure is strong enough. The danger heat transfer condition range which caused by the change of failure region should be avoid in the service as it would lead to a dramatic decrease of the TSR.

Figure 9 corresponds to the active cooling situation (The initial temperature of the plate is 500°C, the heat flux is fixed at 2 MW/m², the temperature of cooling medium is 20°C and the intensity of active cooling is changed to study the effect of active cooling). As it can be seen in Fig. 9:

1. The stronger pneumatic pressure always corresponds to the better TSR when the ZnS plate is imposed with active cooling on its lower surface. That’s because the stress state of the plate (especially the lower surface) is improved as active cooling produces the opposite stress distribution when compared with the situation imposed with heat flux.

2. When the surface heat transfer coefficient is small, damage occurs at the midpoint of the upper surface, and the TSR increases obviously as the surface heat transfer coefficient increases; when the intensity of active cooling is too strong, failure region changes to the lower surface, and the TSR decreases rapidly as the lower surface is destroyed by the active cooling.

So active cooling is an effective way to improve the TSR, but in order to avoid the damage on the lower surface, active cooling can’t be too violent.

5. Conclusions

In this paper, a model of ZnS plate considering the effects of aerodynamic heating, pneumatic pressure and external constraint was established by introducing the analytical solution of transient heat conduction problem of ZnS plate under aerodynamic heating into its thermal stress field model. The thermal shock resistance (TSR) of ZnS plate was studied by both theoretical method and numerical simulation. The influences of constraint and pneumatic pressure were studied and the effects of loosing constraint and active cooling were focused on, so as to give effective suggestions and provide both theoretical basis and technical guidance for the design and application. The theoretical results from the model agree well with the numerical ones.

The study shows that:

1. The critical rupture temperature difference of simply supported ZnS plate will form wave peak (when \( p = 0 \) Pa) and if failure occurs on upper surface, the strong pneumatic pressure corresponds to the better TSR under the same heat transfer condition; if failure occurs on lower surface, the situation is opposite: the stronger pneumatic pressure, the poorer TSR.

2. The TSR of ZnS plate is obviously optimized when loosing constraint method has been adopted, but the danger heat transfer condition range should be avoid in the service as it would lead to a dramatic decrease of the TSR.

3. Active cooling is an effective way to improve the TSR of ZnS plate and the stronger pneumatic pressure, the better TSR. The TSR increases obviously as the surface heat transfer coefficient increases, but in order to avoid the damage on the lower surface, active cooling can’t be too violent.
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