The thermal analysis of the hard X-ray telescope (HXT) and the investigation of the deformation of the mirror foil due to temperature change

Keitaro Ito\textsuperscript{a}, Keiji Ogi\textsuperscript{a}, Hisamitsu Awaki\textsuperscript{a}, Tatsuro Kosaka\textsuperscript{b}, Yasufumi Yamamoto\textsuperscript{a}
\textsuperscript{a} Ehime University, \textsuperscript{b} Kochi University of Technology

**ABSTRACT**

The thin film technology called “depth-graded multi-layer” is used to manufacture reflector foils, which are inserted in a hard X-ray telescope. The foil is constructed of an aluminum substrate, epoxy adhesion layer and a platinum/carbon multi-layered reflecting surface. When the temperature of the foil changes from the temperature at which the foil was produced; thermal deformation is induced due to difference of linear coefficient of expansion of its constituents. The deformation causes performance of X-ray image formation to deteriorate. Therefore, it is absolutely imperative to estimate the amount of deformation quantitatively and to establish a method of temperature control for the foil under the thermal environment on orbit. We used the hard X-ray telescope, which is part of the currently-projected ASTRO-H X-ray satellite, as an example for investigation. The effective method of the HXT “Thermal Desktop” was examined with the thermal analysis of a HXT “Thermal Desktop”. The deformation of the foil when the temperature was changed by 1 degree C was predicated by a finite element analysis (FEA). The experiment on the foil was also performed and the test results were compared with the FEA. The thermal desktop analysis shows that the overall foil temperature in orbit can be close to the temperature at which the foils were produced (~22degree C) by the newly developed thermal control method. The FEM analysis shows that the prediction of the foil deformation due to a temperature change of 1 degree C is about 8 micrometer. We will measure the influence of the deformation on performance of the X-ray image formation in the future.

**Introduction**

Our group is developing a hard X-ray telescope (HXT) as one of the onboard instruments for Astro-H. Since thin films for reflecting X-rays was adhesively bonded inside of the foils, thermal deformation is induced due to mismatch of thermal expansion coefficients of constituent materials when the temperature of the foil is changed from that at manufacturing (295.15 K). Such thermal deformation may cause degradation of quality of the X-ray images. The amount of thermal deformation in the generating line direction must be less than 0.10 mm. Hence, we have to establish the strategy for controlling the temperature of the foils, in addition to determining the allowable temperature range, by predicting thermal deformation of the foils quantitatively.

**Thermal radiation analysis**

**Outline**

The target temperature of the HXT on orbit is ranging from 289.15 K to 297.15 K. In order to analyze the temperature distribution of the housing and foils, a thermo-fluid analysis software “Thermal Desktop” (Ver. 2005) was employed. The Hot and Cold Cases, in which the temperature of the satellite becomes the maximum and minimum, respectively, are considered in the following analysis.

**Analysis 1**

The temperature distribution of the foils when the temperature of the housing is kept at 295.15 K by heater equipped to the housing.

**Analysis 2**

The relationship between the heater power and the average temperature of the housing.

**Analysis model**

The satellite in the model was simplified and simulated by a cylinder. In addition, the satellite was treated as a blackbody in the radiation analysis.

The foils are numbered from the inner to the outer foils.

**The result of analysis 1**

**Analysis conditions**

1. The temperature of the housing was fixed at 295.15 K.
2. The temperature of the satellite was set to be 276.05 K and 296.35 K in the analysis for Cold and Hot Cases, respectively.
3. Radiation between the outer surface of the model and the space, a blackbody at 0 K, was considered.

**The result of analysis 2**

**Analysis conditions**

1. Varying the heat applied to the housing from 0 to 20 W in an increment step of 2.5 W. The total heat applied to the housing was equally divided. The divided heat was then applied to the nodes.
2. The temperature of the satellite was fixed at 276.05 K.
3. Radiation between the outer surface of the model and the space, a blackbody at 0 K, was considered.

The average temperature of the housing becomes 295.15 K when 17 W is given to the housing. The housing is uniformly heated.

**The investigation of the deformation of the mirror foil due to temperature change**

**Outline**

We analyzed the following three cases in order to quantitatively evaluate thermal deformation of the foil.

**Case 1**: free thermal expansion without constraint of deformation.

**Case 2**: thermal expansion with the periodical constraint by the alignment bars.

**Case 3**: both edges of the foil are constrained by the alignment bars.

The real constraint condition is expressed by Case 3.

For Case 1, two-dimensional (2D) and three-dimensional (3D) finite element analysis (FEA) was performed while the curved laminate beam theory was employed for prediction of thermal deformation.

For Case 2, 2D and 3D FEA in addition to prediction using the beam theory was conducted.

For Case 3, only 3D FEA was performed.

**FEA**

Quasi-static thermal deformation analysis was performed using a commercial FE analysis software (Abaqus, Simuca). The 2D model without constraint of the left edge corresponds to Case 1. In contrast, the 3D model, where the deformation in the x-axis direction is negligible in the symmetry planes (curves 2D and 3D), corresponds to Case 1. When the symmetry boundary condition at the curve AC is added to the above boundary conditions, the model corresponds to Case 3. Then, the curve BD represents the central generating line between the alignment bars.

**Measurement of thermal deformation**

The temperature of the foil was controlled by heating or cooling the air in the booth using the heater and the air conditioner. The 3D geometry of the foil at 22, 26 and 30 K was measured, rotating the laser sensor in the horizontal (x) direction from 55 to 65 degrees as well as traversing the sensor in the z-direction.

The data taken from the experiment was transformed to the change in radius of curvature using following equation.

\[ \Delta R = (R - R_0) - \alpha \Delta T \]

### Table: Thickness and material properties of constituent layers

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (µm)</th>
<th>Young’s modulus (GPa)</th>
<th>Poisson ratio</th>
<th>Thermal coefficient of expansion (1/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Housing</td>
<td>0.23</td>
<td>200</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Pre-collimator foil</td>
<td>0.23</td>
<td>300</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Alumite</td>
<td>0.23</td>
<td>400</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>PET</td>
<td>0.23</td>
<td>500</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Satellite</td>
<td>0.23</td>
<td>600</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Top Plate</td>
<td>0.23</td>
<td>700</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Pre-collimator (C/F)</td>
<td>0.23</td>
<td>800</td>
<td>0.32</td>
<td>0.32</td>
</tr>
<tr>
<td>Pre-collimator (ML)</td>
<td>0.23</td>
<td>900</td>
<td>0.32</td>
<td>0.32</td>
</tr>
</tbody>
</table>

**Conclusion**

1. The temperature of the foils is kept at the target temperature by adiabatic housing.
2. The temperature of the secondary foils depends largely on the temperature in the satellite. Hence, it is necessary to control the temperature in the satellite, or to equip the thermal shield at the bottom of the housing.
3. Temperature change must be limited to below 1.8 K for controlling the deformation of the foil along the generating line to less than 0.1 µm.