Thermo-Mechanical Failure Criteria for X-ray Windows and Filters and Comparison with Experiments

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ABSTRACT

Synchrotron x-ray windows are vacuum separators and are usually made of thin beryllium metal. Filters are provided upstream of the window to filter out the soft x-rays to protect the window from overheating and failing. The filters are made of thin carbon products or sometimes beryllium, the same material as the window. Because the window is a vacuum separator, understanding its potential structural failure under thermal load is very important. Current structural failure models for the brazed windows and filters under thermal stresses are not very accurate. Existing models have been carefully examined and found to be inconsistent with the actual failure modes of windows tested.[1-3] Due to the thinness of the filter/window, the most likely failure mode is thermal buckling. In fact, recent synchrotron tests conducted in Japan on window failures bear out this position.[1-2] In this paper, failure criteria for filters/windows are proposed, and analyses are performed and compared with the experimental results from various sources. A consistent result is found between the analysis and reported experiments. A series of additional analyses based on the proposed failure criteria is also carried out for filter and window designs for the third generation synchrotron beamline front ends. Comparative results are presented here.

1. INTRODUCTION: USE OF FILTERS AND WINDOWS IN THE FRONT END DESIGNS

Windows are used to separate different vacuums between the front end and the beamline in synchrotron radiation facilities. Usually, windows are made of a low-atomic-number material so that most of the photons can pass through the window. In order to detect a potential vacuum failure through the window, a double window assembly is used, and a gas like helium fills the space between two windows. However, some insertion devices (IDs) are so powerful that the window itself cannot survive the huge heat load imposed by the beam. Filters are then used to absorb low energy photons before the beam passes through the window. In this case, the window absorbs much less power and can operate safely.

When designing a filter/window assembly, it is very important to use the correct failure criteria and correct analytical method to predict thermal and structural behavior and safety in design of a filter/window assembly subjected to synchrotron x-ray radiation. Many authors[1-6] have performed such analyses and experiments. To predict the failure of the window, a maximum shear stress theory has been widely used,[1-6] which says that when the maximum shear stress becomes equal to half of the yield stress, i.e.,

$$\tau_{max} = \sigma_y/2, \tag{1}$$

this stress state will be in yield, where τ_{max} is the maximum shear stress and σ_y is the yield stress. This theory can be used to predict whether a stress point in the structure goes into yield or not. However, this theory is not successful in predicting the failure of the window assembly. For instance, Shen and others[3] were unable to use the maximum shear stress theory to predict the failure of beryllium windows. At the

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failure load level, the calculated maximum equivalent stress from a finite element code was found to be four times greater than the yield stress for Be window material.

Possible reasons for this discrepancy could be that yielding was not the failure mode in the test. A failure criterion should correspond to the failure mode. When some locations in the structure go into yield, additional load can still be added before the window finally breaks. It should be pointed out that only a one-time load is applied to a tested window while actual working windows will be subjected to many cycles of thermal load during their life times. Under normal working conditions of a filter/window assembly, however, plastic deformation cannot be allowed because the beam will be on and off for many cycles during the life time. Plastic deformation of a window during the working cycle can result in low cycle fatigue. This loading capability can be used as a safety reserve against abnormal situations, such as a sudden increase in the thermal stress due to loss of cooling, for example. Although the tested window exhibits a high one-time load bearing capability, plastic deformation may occur in the window long before the last failure (breakage) of the window. The difference between the load that causes the first occurrence of plastic deformation and the load that causes the last failure of the window in the test may be very large.

When a failure criterion is used in the design and analysis of a structure, the criteria should be consistent with the reason for the actual failure of the structure that happens under the applied load. For example, if a structure could buckle, the typical stress on the structure should be smaller than the buckling stress. If a structure could fracture, a fracture theory should be used to predict the failure. If a structure could fail due to excessive deformation, the deformation caused by the working load should be compared with the allowable deformation. In many cases, a structure can fail in many different ways. Consequently, different failure criteria have to be used to guarantee the safety of that structure. For example, when a pressure vessel is designed according to the ASME pressure vessel and piping code, many different categories of stress as well as different combinations should be checked against different allowable values. These categories and combinations reflect the many different failure phenomena possible for a pressure vessel, such as cracks, low cycle fatigue, plastic deformation, shakedown, etc. In the case of filters and windows, all the possible types of failure should be identified and checked with corresponding criteria. The analyses should give all the information needed by these criteria. Many factors influence the failure modes of the filter/window assembly such as the ratio of thickness to the span of the foil, the filter/window material, load conditions, etc.

This paper is dedicated to the study of failure criteria and analysis models of filter/window structures subjected to synchrotron x-ray radiation. Appropriate failure criteria are proposed based on the study of failure mode, and analytical methods were developed. Predictions are compared with the available experimental results. The proposed failure criteria and analysis methods are then used for filter and window design and analysis for the Advanced Photon Source (APS) undulators, wigglers, and bending magnet devices. Conclusions on failure and survival of the windows are offered.

2. FAILURE CRITERIA AND ANALYSIS METHODS FOR THE FILTER AND WINDOW ASSEMBLY

When the filter/window absorbs radiation, the temperature in these components rises. Due to thermal expansion, compression stresses are produced. The larger the temperature difference, the larger the compression stresses. At a certain level of compression stress, the structure buckles. Also the tensile stress at the boundary or due to bending in the assembly can cause breakage. High temperatures in the assembly can cause melting or evaporating of the filter/window or an excessive amount of outgassing. When designing a filter/window assembly, one should satisfy at least two categories of criteria. First, the maximum temperature should be less than the melting or sublimation temperature of the material at designed vacuum and less than the maximum outgassing temperature with some proper safety margin. Second, the stress state should be within a proper safety margin.

The first category is straightforward. The second category guarantees structural integrity of filter/window. To do so, we have to guard against all possible failures. These possible failures include:

excessive deformation of the assembly; low cycle fatigue due to plastic deformation in each loading and unloading cycle; possible breakage due to excessive tensile stress or strain; and elastic or plastic buckling of the filter/window due to excessive compression stress in filter/window.

From the above discussion, the following failure criteria are proposed for the filter/window design and analysis:

1. For a filter and window assembly, the design of materials and thicknesses of filter and window should satisfy the criteria that the number of photons at the minimum usable energy be larger than a certain fraction of the total, i.e., the original photon count, before passing through the assembly:

$$P_{E\min} \prod_{n} f^{i}{}_{E\min} \geq k P_{E\min},$$

where E_{min} is the minimum photon energy to be used, P_{Emin} is the total number of photons at energy E_{min}; and k is the fraction that, by design, must pass through the filter/window assembly; $f^i{}_{Emin}$ is the photon transmission at energy E_{min} through the ith filter/window; n is the total number of filter/windows. The factor k and the minimum energy E_{min} are decided by the beamline users. Canceling of P_{Emin} from both sides of the above equation yields:

$$\prod_{n} f^{i}{}_{E\min} \geq k . \qquad (2)$$

2. The maximum temperature T_{max} of the filter/window should be less than the larger of the following: T_m, the melting or sublimation temperature of the material at the designed vacuum and T_0, the temperature at which outgassing becomes unacceptable. In other words, the following criteria have to be satisfied for a successful design:

$$T_{max} < \max\{T_m, T_0\}. \qquad (3)$$

3. The maximum von Mises stress or equivalent stress σ_{max} should be smaller than the yielding stress of the filter/window material σ_s:

$$\sigma_{max} < \sigma_s. \qquad (4)$$

This is equivalent to equation (1) and will guarantee that no low cycle fatigue occurs under normal working conditions. An alternative of this criterion is that the structure should shakedown, that is, after a certain number of load cycles, there will be no plastic deformation in the structure due to residual stress caused by previous plastic deformation. Usually, the shakedown load is larger than the load that initiates plastic deformation in the structure.

4. The maximum tensile stress σ_{tmax} should not surpass the tensile strength of filter/window material σ_t:

$$\sigma_{tmax} < \sigma_t, \qquad (5)$$

which ensures that the material will not break. This is extremely important for filters/windows made of low-tensile-strength material, such as carbon. For ductile material, the maximum tensile strain ε_{tmax} should be less than the allowable tensile strain ε_t:

$$\varepsilon_{tmax} < \varepsilon_t. \tag{6}$$

5. The maximum deformation of the filter/window assembly Δ_{max} should be less than the allowable deformation Δ_a:

$$\Delta_{max} < \Delta_a. \tag{7}$$

6. Buckling should not occur under normal working conditions. Buckling can be checked in many ways, such as finite element analysis or analytical methods based on simplified models that give a good estimation. For example, if the two maximum compression stresses σ_x and σ_y are about the same, then the larger one (of σ_x and σ_y) has to be smaller than the buckling stress:

$$\max\{\sigma_x, \sigma_y\} < \sigma_b, \tag{8}$$

where σ_b can be given by Timoshenko[7]

$$\sigma_b = 4.82\, E(t/h)^2 \tag{9}$$

for a clamped square plate, and

$$\sigma_b = 3.3\, E(t/h)^2 \tag{10}$$

for a clamped rectangular plate, if the ratio of the width and the height of the window is large enough. Here, t is the thickness, h is the height of the filter/window, and E is the Young's modulus of the filter/window material. For a clamped edge square plate with one-dimensional uniform compression, σ_b is given by

$$\sigma_b = 9.10\, E(t/h)^2. \tag{11}$$

For a rectangular plate with different compression stresses σ_x and σ_y, some calculations are needed to get σ_b. One can use the following equation[7]:

$$\left(\sigma_x + \frac{a^2}{b^2}\sigma_y\right)_{cr} = \frac{4}{3}\frac{\pi^2 D a^2}{h}\left(\frac{3}{a^4} + \frac{3}{b^4} + \frac{2}{a^2 b^2}\right). \tag{12}$$

If the maximum compression stress is equal to σ_b when the maximum von Mises stress is larger than σ_s, plastic buckling will occur, which will cause irreversible plastic deformation. If the maximum compression stress is larger than σ_b but the maximum von Mises stress is less than σ_s, elastic buckling will occur. Buckling can cause breakage due to excessive bending after buckling.

7. Materials used in the filter/window assembly should not pose a "hot-spot" effect on the filter/window. The "hot-spot" effect is caused by material impurity. It means that, at a very small part of the material, the absorption of photons is significantly higher than at other parts of the material. The "hot-spot" effect should be avoided by material specifications in the design.

All the load cases and their combinations should be considered when applying the above failure criteria. For example, the possible air pressure should be considered in the stress analysis for a window that is exposed to a pressure difference. The pressure-induced stress should be evaluated separately and/or in combination with other stresses such as thermal stress from absorbed power.

3. COMPARISON WITH TEST DATA AND EXISTING DEVICES

In this section, the above proposed failure criteria and suggested design and analytical methodology is used to compare with test data of windows and the HASYLAB data.

3.1 Comparison with tests from Maezawa and others[1,2]

Tests by Maezawa and others[1,2] were performed on two 0.3-mm Be window assemblies with an aperture of 120 X 10 mm. The heat load was generated by Photon Factory BL-16A wiggler/undulator. The Be windows were at 16.85 m from the source. One window was made of hot-pressed Be ribbon and the other one of cross-rolled Be ribbon. The absorbed power was in the range of 27.5 W to 600 W. The tests showed that one window buckled due to thermal stress from the absorbed power, and the other buckled then evaporated. These tests[1,2] showed that, at failure, the temperature difference on the windows was about 200 ^{0}C, and the corresponding maximum thermal stress was 810 MPa.

To verify the proposed failure criteria and analysis methodology in Section 2, a series of analyses were performed using the data from these references[1,2] and then compared with the test data. Both finite element analysis and analysis using analytical formula were performed. By assuming that the stress in the window is uniformly distributed and that the stresses in horizontal and vertical direction are the same, one can check the buckling of the window by substituting the following parameters into equation (10):

$h = 1.0$ cm, $t = 0.03$ cm, $E = 29 \times 10^6$ N/cm^2.

The buckling stress is

$$\sigma_b = 3.3 \times 29 \times 10^6 \times (0.03/1.0)^2 = 86130 \text{ N/cm}^2 = 861.3 \text{ MPa},$$

which agrees very well with calculation of thermal stress, i.e., 810 MPa, by Maezawa et al.

A more precise analysis was also performed by finite element method. First, the total absorbed power on a 300-micron-thick Be window was calculated. A thermal analysis for case A, which is corresponding to buckling load level in references[1,2], is then carried out. The temperature profile along the vertical axis is in very good agreement with the data.[1,2] The thermal buckling analysis was then carried out for this case. The buckling load factor was found to be about 0.85 to 0.9. This is consistent with the experimental results.[1,2]

The good agreement between analysis results and test data clearly shows that the correct failure criteria should be used when one is designing and analyzing the filter/window structure.

3.2 Comparison with tests from Shen and others[3]

Tests by Q. Shen and others[3] featured a 0.25-mm Be window with an aperture of 50 X 6 mm. The test load was a 45 X 5 mm electron beam, starting from 100 W and ramped up in 20 W increments. The window cracked at 660 W. Analysis[3] showed that the maximum equivalent stress was 1600 MPa, while the yielding stress of the Be window material is 345 MPa, about a four times difference if Eq (1), that is, the maximum shear stress theory, is used to predicate the failure instead of using a buckling check of the window. By using the maximum distortion energy theory, the window should have failed at about 200 W according to Shen et al.[3]

Using the failure criteria proposed in this paper, a check of buckling can be carried out on the window by substituting the following parameter into equation (10):

$h = 0.6$ cm, $t = 0.025$ cm, $E = 29 \times 10^6$ N/cm^2.

The buckling stress is

$$\sigma_b = 3.3 \times 29 \times 10^6 \times (0.025/0.6)^2 = 166145 \text{ N/cm}^2 = 1661 \text{ MPa},$$

which agrees very well with Shen's calculation[3] of thermal stress, i.e., 1600 MPa. This shows that the window indeed buckled at 660 W of heat load.

3.3 Comparison with an existing device[7]

A comparative analysis based on the above methodology has also been performed on a HASYLAB Doris graphite/Be window assembly.[7] The assembly has been in operation for a long time and has no known problems. The filter thickness is 0.13 mm, and the window thickness is 1 mm. The size of the window is 15 mm X 80 mm. The total absorbed power on the window is 410 W. Thermal analyses from this paper show that the maximum temperature of the window is 172.7 ^{0}C, and the minimum temperature is 97 ^{0}C. The temperature difference is 75.7 ^{0}C. The maximum von Mises stress from thermal stress analysis is 265 MPa, less than the yielding stress for the material, 300 MPa. The maximum compression stress in the horizontal direction is 293 MPa, and the maximum compression stress in the vertical direction is 223 MPa. Therefore, the assembly is proved to be safe from the analysis, which is consistent with the actual filter/window assembly performance.

A second analysis then was performed for the same filter but with only a 0.4-mm-thick Be window. The total absorbed power on the window is 200 W. The maximum temperature of the window is 141.6 ^{0}C, and the minimum temperature is 60 ^{0}C. The maximum von Mises stress from the thermal stress analysis is 278 MPa, also less than the yielding stress of Be material. The maximum compression stress in the horizontal direction is 312 MPa and in the vertical direction is 222 MPa. The buckling load factor is about 2.07. The buckling stress is 704 MPa from equation (9), which agrees with the figure found using finite element analysis (312 MPa X 2.07 = 645 MPa). This suggests that, by changing the window thickness from 1.0 mm to 0.4 mm the assembly is still safe, and the safety margin has not changed much: it is 1.13 for a 1.0-mm window and 1.08 for a 0.4-mm window. This can be explained by fact that, by putting enough filter in front of the window, the absorbed power on window will be proportional to the thickness of the window and, hence, the thermal and structural behavior will almost remain unchanged if no buckling occurs.[10]

The comparative analysis of the filter/window design in HASYLAB has shown that the above design criteria are consistent with the performance of existing filter/window assemblies, and the above failure criteria can define the safety domain of the assembly.

4. WINDOW AND FILTER DESIGN FOR APS BEAMLINES

The proposed failure criteria have been used for APS filter and window design. Thermal and structural analyses have been performed for various thicknesses of filter and Be window and to determine the materials for the filter/window assembly from possible candidate materials. It has been determined that a graphite filter with a Be window is a good combination of materials for the APS filter/window assembly. Analyses are then performed to check against all the failure criteria.

4.1 Graphite Filter and Be Window Assembly for an APS Undulator

Thermal analyses were carried out for the filters and windows. The heat load used is from the most powerful APS undulator (Undulator A).

In order to satisfy all the failure criteria in Section 2, analyses were performed for different thickness of graphite filter and a Be window with different device gap sizes. For each gap size, thermal and structural analyses are performed for the graphite filter and Be window separately. If either filter or window cannot satisfy any of the criteria in Section 2, the next gap size is analyzed. The analysis will continue until the corresponding graphite filter thickness can also make the window safe.

Table 1 Analysis results of filter and window for undulator

Distance from Source (m)	24
Total Power (W)	1867
Absorbed Power on Filter (W)	484
Absorbed Power on 1st Be Window (W)	25
Absorbed Power on 2nd Be Window (W)	23
Max Temperature on Filter (^{0}K)	1741
Max von Mises Stress on Filter (MPa)	13.52
Max Tensile Stress on Filter (MPa)	2.45
Max Compression Stress on Filter (MPa)	-15.16
Max Temperature on 1st Window (^{0}C)	134.8
Min Temperature on 1st Window (^{0}C)	29.3
Max von Mises Stress on 1st Window (MPa)	273.5
Max Compression Stress on 1st Window (MPa)	284.4
Buckling Load Factor of 1st window	2.08
Max Temperature on 2nd Window (^{0}C)	124.2
Min Temperature on 2nd Window (^{0}C)	28.9
Max von Mises Stress on 2nd Window (MPa)	287.7
Max Compression Stress on 2nd Window (MPa)	315.9
Buckling Load Factor of 2nd Window	10.9

Table 1 lists the thermal and structural analysis results for filter and window. From the table, it can be seen that, with a 280-mm graphite filter and two Be windows at a device gap of 1.5 cm, no structural failure is predicted under normal working conditions. The filter/window assembly can satisfy all the criteria in Section 2 under the assumption that 50% of photons at the first harmonic can pass through the assembly. Because the stress level in both windows is at the level of the yielding stress of the Be material while the buckling load factor is two or larger, the failure mode will be plastic deformation or plastic-deformation-induced low-cycle fatigue. Due to the plasticity of the Be material, the windows can tolerate an abnormal temperature jump over normal temperature of a factor of two.

4.2 Graphite Filter and Be Window Assembly for a Wiggler

By using the criteria in Section 2, we can roughly estimate the optimum thickness of the window to be such that the buckling stress equals the yielding stress:

$$t = h\sqrt{\frac{\sigma_s}{3.3E}} \cong 0.21mm.$$

A window thinner than this value will undergo elastic buckling. A window thicker than this will block more photons without increasing in the safety margin. To consider the divergence and other factors, we use t = 0.25 mm for the tentative thickness of the Be window. The window and filter analyses are then carried out based on the APS Wiggler AIII parameters. APS Wiggler AIII is the most powerful wiggler currently designed at the APS.

If a 0.30-mm graphite filter is used in the front of the Be window and the filter is assumed to be clamped and its frame is cooled by water, thermal analysis reveals that the maximum temperature on filter is 2012 ^{0}K and the maximum von Mises stress is 29.73 MPa, the maximum compression stress is 29.7 MPa, and the maximum tensile stress is only 2.17 MPa. For graphite material, there will be no sublimation problem at 2000 ^{0}C under a vacuum of 10^{-7} mm Hg.[12] Because only high energy photons are to be used and most photons above 10 keV pass through the assembly, there is no minimum filter thickness requirement. The maximum stress level is below the tensile strength, the compression strength, and the buckling stress of graphite material.

Thermal analysis on a 0.25-mm Be window shows that the maximum temperature on the window is 136 ^{0}C, and the maximum temperature difference is 91^{0}C. Large deformation nonlinear thermal stress analysis then is performed using the temperature field from the thermal analysis. The maximum von Mises stress is 317 MPa, and the maximum compression stress is 326 MPa. The corresponding buckling factor is 1.63. As expected, the window yields first, then it goes to plastic buckling.

Buckling can also be checked by analytical formula equation (10) under the assumptions that the stresses in the window are uniform and both vertical direction stress and horizontal direction stresses are equal. Substituting the height h = 1 cm and window thickness = 0.025 cm into equation (10) (for the buckling stress of a rectangular plate with all edges clamped) yields:

$$\sigma_x = 3.3\ Et^2 = 662\ \text{MPa},$$

which agrees well with the finite element result of 317 MPa X 1.63 = 516 MPa.

Note that the maximum temperature of the Be window is far below the melting temperature of the material and poses no outgassing problem at 217 ^{0}C. With a 0.3-mm graphite filter, all the failure criteria have been satisfied and the filter/window assembly can operate safely.

4.3 Graphite Filter and Be Window Assembly for a Bending Magnet

Analysis of a 0.25-mm Be window was performed based on the APS bending magnet with 300 mA current. The absorbed power is very small. Even when twice the absorbed power was imposed on the window, the maximum temperature is only about 70 ^{0}C, and the temperature increment on the window is 30 ^{0}C. The corresponding thermal stress shows that the maximum compression stress is only about 106 MPa, and the maximum von Mises stress is 95 MPa. Both are far below the yielding stress and the buckling stress. Thus the APS bending magnet front ends can function with a single Be window and require no filter.

5. CONCLUSIONS AND SUGGESTIONS

A set of failure criteria is proposed in this paper, and these failure criteria have been successfully used to predict the failure mode of tests[1-3] and the behavior of existing filter and window devices.[9] The failure criteria is also used to analyze and design filters and windows for the APS.

It has been shown that in design and analysis of a filter/window assembly, all possible failure modes should be identified and corresponding failure criteria should be used for each of the failure modes. In the case of thin shell-like structures, the typical failure mode is more likely buckling. It is very important to do a buckling analysis when designing such thin filters or windows.

Because there may be many other uncertainties and unknowns in the analysis, it will be a good practice to verify the analytical model with test data and to compare the model with existing filter/window assemblies and analytical results from other sources.

Because thermal stress in the window is strain controlled, the lateral deformation of window due to buckling might relax the thermal stress. Therefore one might suggest that elastic buckling could be allowable under normal working conditions of the window. However, a careful study including experimental verification should be carried out, and a larger deformation postbuckling analysis has to be performed to make sure this argument is true before the postbuckling behavior can be considered in the design. The postbuckling behavior will be discussed in a separate paper.[13]

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