Mechanical research and development of a monocrystalline silicon neutron beam window for CSNS

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Abstract: The monocrystalline silicon neutron beam window is one of the key components of a neutron spectrometer. Monocrystalline silicon is brittle and its strength is generally described by a Weibull distribution due to the material inhomogeneity. The window is designed not simply according to the mean strength but also according to the survival rate. The total stress of the window is stress-linearized into a combination of membrane stress and bending stress by finite element analysis. The window is a thin circular plate, so bending deformation is the main cause of failure and tensile deformation is secondary and negligible. Based on the Weibull distribution of bending strength of monocrystalline silicon, the optimized neutron beam window is designed to be 1.5 mm thick. Its survival rate is 0.9994 and its transmittance is 0.98447, which meets both physical and mechanical requirements.

Key words: neutron beam window, monocrystalline silicon China Spallation Neutron Source the survival rate, neutron spectrometers

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1 Introduction

For the China Spallation Neutron Source (CSNS), neutrons pass through a vacuum environment as far as possible. As with most neutron spectrometers, the CSNS has neutron beam windows that are used as entrances or exits of certain neutron paths [1]. Neutron beam windows are key components which have the ability to let neutrons pass with limited loss and little neutron background. There are mainly three kinds of materials for beam windows: monocrystalline silicon, sapphire, and aluminum alloy. Monocrystalline silicon is the best material. On the one hand, for physics reasons, a neutron beam window should be designed to be as thin as possible. On the other hand, the window must be thick enough to resist the pressure caused by the vacuum environment. Therefore, the development of neutron beam windows that can meet both physical and mechanical requirements is essential for all neutron spectrometers.

2 Key development issues

A prototype neutron beam window for CSNS was made of monocrystalline silicon that was 40 mm in diameter and 0.5 mm thick, as shown in Fig. 1. In order to protect the monocrystalline silicon, there are rubber sealing rings on either surface, and so the silicon window only has an indirect contact with the metal flange. The basic mechanical properties of monocrystalline silicon [2] are shown in Table 1.

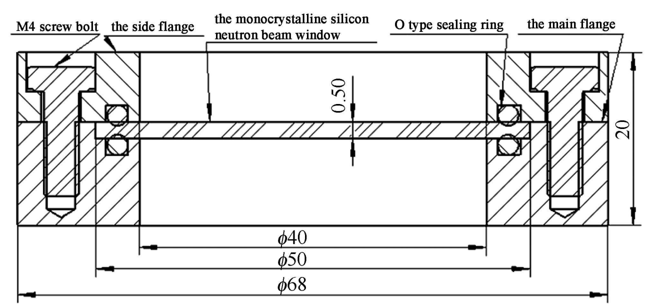

Fig. 1. Prototype monocrystalline silicon neutron beam window.

Deformation of the prototype window is modeled with finite element analysis. In order to simplify modeling of the deformation process, the window is considered as a thin circular plate of simply supported wafer with uniform load impact. According to the results, as shown in Fig. 2, the maximum equivalent stress is 138.3 MPa under one atmospheric pressure, which is well under the tensile strength (350 MPa) of monocrystalline silicon.

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Table 1. Basic mechanical properties of monocrystalline silicon.

density (293 K)	shear strength	tensile strength	compressive strength	bending strength	Young's modulus	Poisson's ratio
2.327 g/cm^3	240 MPa	350 MPa	950 MPa	300 – 1000 MPa	$E_{[100]}$=1.30e5 MPa	$P_{[100]}$=0.278
					$E_{[110]}$=1.68e5 MPa	$P_{[110]}$=0.25
					$E_{[111]}$=1.87e5 MPa	$P_{[111]}$=0.20

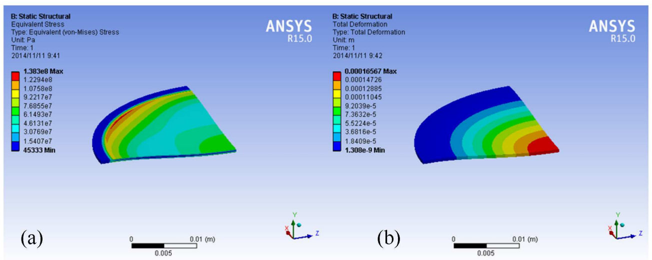

Fig. 2. (color online) Finite element analysis results for monocrystalline silicon neutron beam window (0.5 mm thick) under one atmospheric stress.

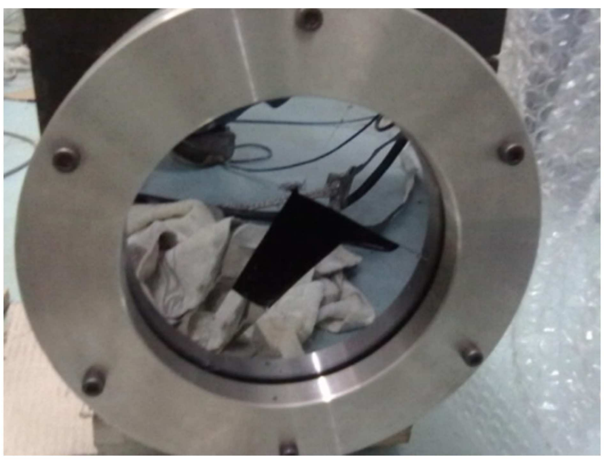

Fig. 3. (color online) Broken monocrystalline silicon neutron beam window.

The maximum displacement is less than 0.166 mm. However, the prototype window broke during the process of vacuum extraction, as shown in Fig. 3.

3 Causes of failure

Monocrystalline silicon is brittle and the neutron beam window is a thin circular plate. The bending strength is not constant but has a statistical distribution; generally, a Weibull distribution is used to describe the bending strength of brittle materials [3, 5]. Under some bending stress σ_b the window's failure rate is:

$$F(\sigma_\mathrm{b})=1-\exp\left[-\left(\frac{\sigma_\mathrm{b}}{a}\right)^m\right]. \tag{1}$$

The survival rate is:

$$P=\exp\left[-\left(\frac{\sigma_\mathrm{b}}{a}\right)^m\right]. \tag{2}$$

And then the equation of the survival rate is linearized as

$$\ln\ln\frac{1}{p}=m\ln\sigma_\mathrm{b}-m\ln a. \tag{3}$$

And then b, x, y are defined as

$$b = m\ln a, \tag{4}$$

$$x = \ln\sigma_\mathrm{b}, \tag{5}$$

$$y = \ln\ln\frac{1}{p}. \tag{6}$$

So the linearized equation is:

$$y=mx-b, \tag{7}$$

m is the heterogeneity, which is used to measure the material inhomogeneity: the greater the m value is, the more homogeneous the material is. a is the eigenvalue, which is used to approximately represent the mean value $E(\sigma_\mathrm{b})$ of the window bending strength:

$$E(\sigma_\mathrm{b})=a\Gamma\left(1+\frac{1}{m}\right). \tag{8}$$

$\Gamma\left(1+\frac{1}{m}\right)$ is a function:

$$\Gamma\left(1+\frac{1}{m}\right)=\int_0^\infty Z^{\left(1+\frac{1}{m}\right)-1}\mathrm{e}^{-Z}\mathrm{d}Z. \tag{9}$$

Table 2. Bending strengths (MPa) of different thicknesses (mm) of neutron beam windows (40 mm in diameter).

0.25	0.3	0.5	0.6	0.75	0.9	trend value
132.4	135.3	147.1	147.1	147.1	147.1	147.1
160.8	164.8	180.4	186.3	196.1	196.1	196.1
183.9	193.7	215.8	223.1	237.8	245.2	245.2
211.8	217.7	250.1	261.8	276.6	294.2	294.2
236.8	243.7	278.0	295.2	319.2	339.8	343.2
258.9	270.7	309.9	329.5	357.0	380.5	392.3
286.9	295.7	339.8	357.5	392.8	423.7	441.3
313.8	323.6	367.8	392.3	426.6	460.9	490.3
334.4	350.6	393.7	420.7	458.5	501.6	539.4
364.8	376.6	423.7	453.1	494.3	535.4	588.4
395.2	401.6	452.6	478.1	522.7	573.7	637.4
418.8	432.5	480.5	508.0	556.0		686.5
448.7	463.4	507.5	536.9			735.5
478.6	494.3	533.5	564.9			784.5
508.5	525.2	566.8	591.8			833.6
538.4	556.0	600.2	626.7			882.6
568.3	586.9					931.6
597.8	617.4					980.1

A simply supported wafer with concentrated load impact is applied to measure the bending strength of the neutron beam window [4]. Some bending strengths of different thickness of neutron beam windows from GB/T15615-1995 are shown in Table 2. The bending strength of the neutron beam window becomes smaller due to the size effect when the window becomes thinner. When the window becomes thicker, the bending strength becomes bigger, and it finally trends to a constant value (the size effect becomes negligible). The trend value is the bending strength of the material itself.

For example, when the thickness is 0.9 mm, the data of the bending strength is reordered from high to low in Table 3. According to mean rank order, the survival rate is: $p=\frac{i}{N+1}$. The result of fitting the data from Table 3 using Origin software is shown in Fig. 4, and the equation is:

$$y=2.3065x-13.974. \tag{10}$$

Other equations of the survival rate for different thicknesses are obtained by the same method. The result is shown in Table 4.

Table 3. Bending strength and survival rate of 0.9 mm thick neutron beam window.

serial number $i(1{:}N)$	bending strength/MPa	survival rate
1	573.7	0.083333
2	535.4	0.166667
3	501.6	0.25
4	460.9	0.333333
5	423.7	0.416667
6	380.5	0.5
7	339.8	0.583333
8	294.2	0.666667
9	245.2	0.75
10	196.1	0.833333
11	147.1	0.916667

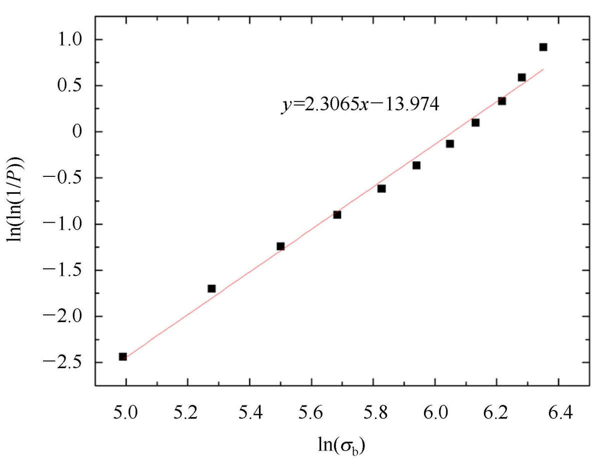

Fig. 4. (color online) Fitting curve of bending strength and the survival rate of a 0.9 mm thick neutron beam window.

The homogeneity degree of 1.9138 is the minimum value of neutron beam windows. The window will be most reliable if it is designed according to the extreme situation of the minimum homogeneity degree, in which case the survival rate is:

$$p=\exp\left[-\left(\frac{\sigma_{\mathrm{b}}}{650.44}\right)^{1.9138}\right]. \tag{11}$$

Table 4. Equations of survival rate for different thicknesses of silicon neutron beam window (40 mm in diameter).

thickness/mm	m	b
0.25	2.3705	−14.246
0.30	2.3075	−14.323
0.50	2.5171	−15.263
0.60	2.4505	−14.994
0.75	2.4530	−14.802
0.90	2.3065	−13.974
trend value	1.9138	−12.397

Because the monocrystalline silicon window is a thin circular plate, bending deformation is the main cause of failure and tensile deformation is secondary and negligible. The stress of monocrystalline silicon window is equivalent to the combination of membrane stress and bending stress [6]. The weak spots of the neutron beam window were then stress-linearized by finite element analysis, the result for a 0.5 mm thick window is shown in Fig. 5. According to these results, the maximum bending stress is about 115 MPa and the maximum membrane stress is about 20 MPa, which is negligible in comparison with the bending stress. So the survival rate is 0.9644. This means that one out of thirty windows will break, as happened to the prototype. Therefore, the window needs to be made thicker.

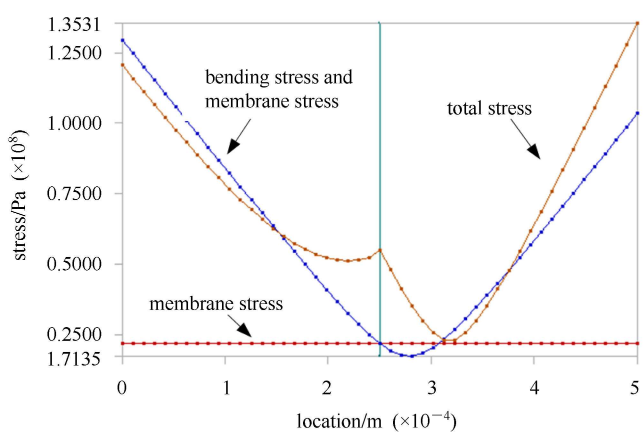

Fig. 5. (color online) Stress-linearization of a monocrystalline silicon neutron beam window (0.5 mm thick).

4 Optimization of the thickness of monocrystalline silicon neutron beam window

As shown in Fig. 6, when the monocrystalline silicon window thickness is increased to 1 mm, the maximum equivalent stress is 38.9 MPa, and the maximum displacement is 22 microns.

Then weak spots of the neutron beam window were then stress-linearized, and the result is shown in Fig. 7. According to the result, the maximum bending stress (σ_{bmax}) is about 30 MPa. So the survival rate is 0.9972. This means that about three out of one thousand windows will break.

The mean value of the window bending strength is:

$$E(\sigma_{\mathrm{b}}) = a\Gamma\left(1+\frac{1}{m}\right)=650.44\times\Gamma\left(1+\frac{1}{1.9138}\right) \approx 577.04\ \mathrm{MPa}. \tag{12}$$

And the mean variance of the window's bending strength is:

$$D(\sigma_{\mathrm{b}}) = a\sqrt{\left[\Gamma\left(1+\frac{2}{m}\right)-\Gamma^2\left(1+\frac{1}{m}\right)\right]} = 650.44\times\sqrt{\left[\Gamma\left(1+\frac{2}{1.9138}\right)-\Gamma^2\left(1+\frac{1}{1.9138}\right)\right]} \approx 300.31\mathrm{MPa}. \tag{13}$$

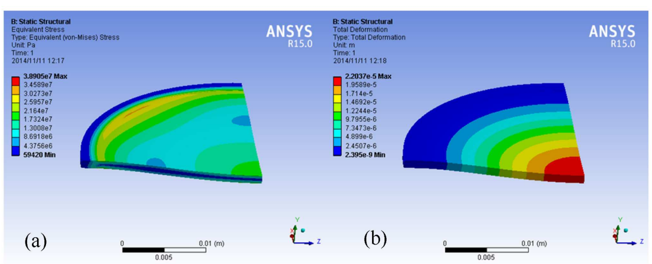

Fig. 6. (color online) Finite element analysis results of a monocrystalline silicon neutron beam window (1 mm thick) under an atmospheric stress.

Comparing with the mean value of the window bending strength, the mean variance is non-negligible. Therefore, the window is designed not simply according to the mean strength but also according to the survival rate. Therefore, if designed in accordance with the mean value of the window's bending strength, the safety coefficient is:

$$\lambda=\frac{E(\sigma_{\mathrm{b}})}{\sigma_{\mathrm{bmax}}}=\frac{577.04}{30}\approx 19.24. \tag{14}$$

The value of the safety coefficient outweighs 2–4 used in the design of metal windows. If a broken window can be replaced quickly and conveniently without affecting the whole operation of the spectrometer, a 1 mm thick window is acceptable.

If the replacement procedure is not easy and convenient, and if it will affect the whole operation of the spectrometer, then the silicon window thickness should be increased to 1.5 mm, as shown in Fig. 8. In this case, the maximum equivalent stress is 20.2 MPa and the maximum displacement is 8 microns.

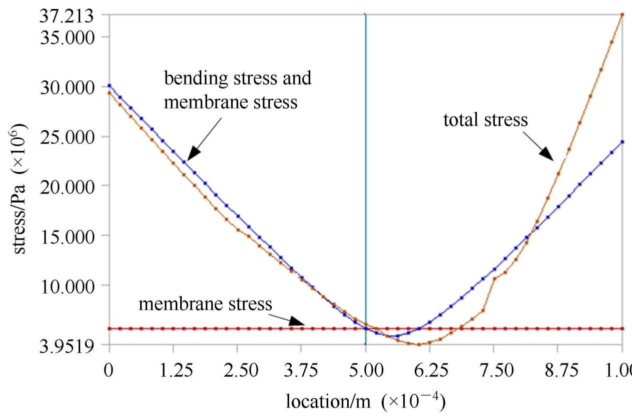

Fig. 7. (color online) Stress-linearization of monocrystalline silicon neutron beam window (1 mm thick).

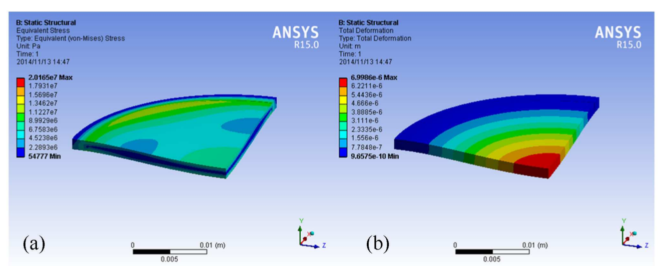

Fig. 8. (color online) Finite element analysis results of monocrystalline silicon neutron beam window (1.5 mm thick) under an atmospheric stress.

The weak spots of the neutron beam window with 1.5 mm thickness were then stress-linearized, and the result is shown in Fig. 9. According to the result, the maximum bending stress (σ_{bmax}) is about 13.1 MPa, so the survival rate is 0.9994. A 1.5 mm thick window is strong enough to withstand most stress, only one out of every 1667 windows will break. Therefore, if the design is in accordance with the mean value of the window's bending strength, the safety coefficient is:

$$\lambda=\frac{E(\sigma_{\mathrm{b}})}{\sigma_{\mathrm{bmax}}}=\frac{577.04}{13.1}\approx 44.05. \tag{15}$$

Comparing 1.5 mm thick window with a 1 mm thick window, the survival rate is increased by 0.0022 but the

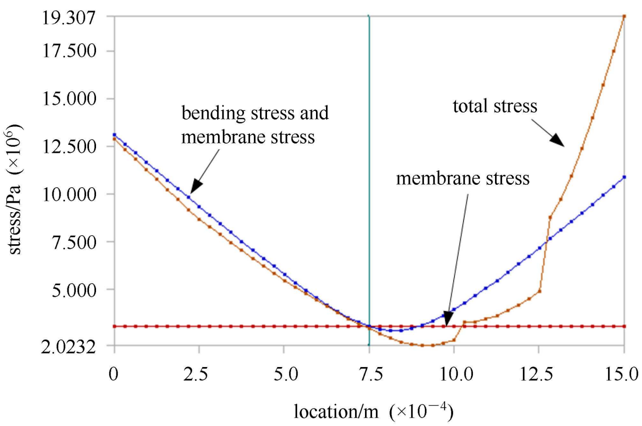

Fig. 9. (color online) Stress-linearization of monocrystalline silicon neutron beam window (1.5 mm thick).

safety coefficient is increased about 2.29 times. Therefore the survival rate can reflect the real situation more accurately than the safety coefficient.

The transmittance of a 1.5 mm thick silicon neutron beam window is 0.98447, which meets the physics requirements. In light of the cost, only 20 neutron beam windows were tested, but none of them broke. The mechanical strength requirements are, therefore, considered satisfied.

5 Conclusion

The monocrystalline silicon neutron beam window is a thin circular plate. Comparing bending stress with membrane stress, bending deformation is the main cause of failure while membrane stress is secondary and negligible. Basing on the Weibull distribution of bending strength of monocrystalline silicon, the thickness of the neutron beam window is optimized to be 1.5 mm. The survival rate of the optimized window is 0.9994 and the transmittance of the window is 0.98447. This meets both physical and mechanical requirements.

The material inhomogeneity has been considered when designing a monocrystalline silicon neutron beam window for CSNS. This will provide a reference for developing sapphire neutron beam windows in the future.

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