QUALIFICATION OF A GLASSY CARBON BLADE FOR A LHC FAST VACUUM VALVE

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Abstract

To protect sensitive LHC machine systems against an unexpected gas inrush, a fast vacuum valve system is under development at CERN. The design of the shutter has to be compatible with dynamic loads occurring during the fast closure, namely in the 20 ms range. The material has to fulfil all main requirements such as transparency, high melting temperature, dust free and adequate leak tightness. A development of a blade in vitreous carbon material has been carried out at CERN. The blade has been successfully integrated in a commercial pendulum fast valve. In this paper, the vacuum and mechanical qualification tests are presented.

INTRODUCTION

The development of a fast shutter valve with a transparent blade material has been carried out. The glassy carbon has been chosen for this part and its design, driven by the brittleness material properties, has been presented in a previous paper [1]. The fast shutter is presented in Fig. 1. It is based on a pendulum motion of a disc embedded in a titanium support. Both are guided between 2 planes. A pneumatic actuator is used. With this design, the disc could be in any material depending on the application requirements. In the closed position, the disc is concentric with the valve aperture. In case of a differential pressure across the disc, this arrangement leads to a uniform disc deformation and therefore higher reliability and higher leak tightness.

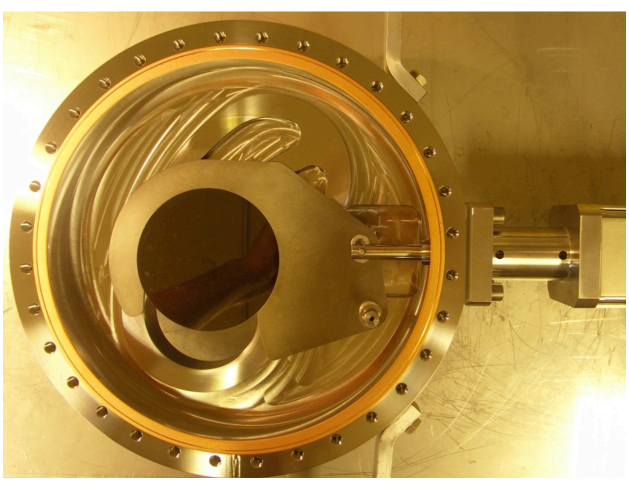

Figure 1: Picture of the fast valve partially opened.

The disc has been extracted by electrical discharge wire cutting from a glassy carbon plate, 2 mm thick, grade G, provided by HTW*. The sharp edges are slightly rounded with fine abrasive paper to avoid chipping. A small interference fit of 0.1 mm in diameter retains the disc in the titanium holder.

VACUUM TESTS

Material Thermal Outgassing

The thermal outgassing of the glassy carbon has been evaluated for the 2 grades supplied by HTW. The grades K and G are obtained after a pyrolysis at 1000 °C and 3000 °C, respectively. First outgassing tests have been carried out considering pump down curves through a diaphragm with a conductance of 2.3 l/s. The outgassing of the grade K, even after a heat treatment at 800 °C for 10 hours, is significant and is dominated by water. The surfaces of the samples are 1 and 4 cm^2 for the grade K and G, respectively. The pump down curve for the grade G is similar to the background curve, meaning a low outgassing rate. To evaluate more precisely the thermal outgassing rate of the grade G glassy carbon, accumulation tests have been carried out on a Fisher-Mommsen dome. Tests are done with different accumulation times done after a bake out cycle at 150 °C for around 2 hours. The accumulated gas quantities are given in Fig. 2 for different species [2].

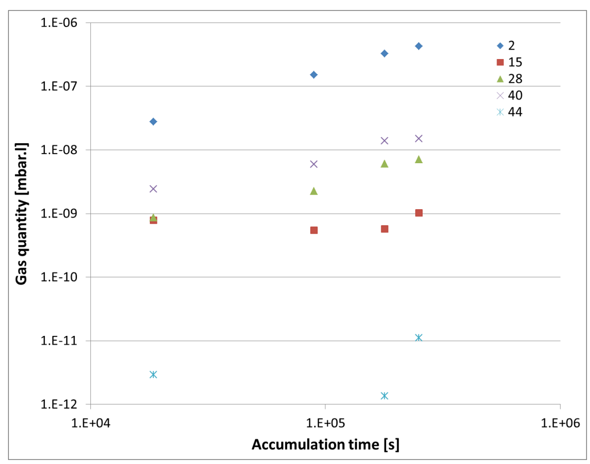

Figure 2 Accumulated gas as a function of time for different species.

The thermal outgassing is driven by hydrogen. A linear regression is used to evaluate the outgassing rate. It is around $2.5.10^{-13}$ $mbar.l.s^{-1}.cm^{-2}$ for hydrogen.

Leak Rate as a Function of Seat Radius and Surface State

The leak tightness of the valve is obtained by direct contact between the glassy carbon disc and the stainless

* HTW Hochtemperatur-Werkstoffe GmbH, Thierhaupten, Germany

steel seat. Leak rate measurements have been carried out for different discs and with different fillet radii of the seat (~0.2, 1, 1.5, 2 and 2.5 mm). For the same disc, the fillet radius doesn't have any significant influence. The leak rate is driven by the disc surface state and varies between 1 to 10^{-3} mbar.l/s with a differential pressure of 1 bar. The flatness of an as-received plate may be in the order of 0.1 mm [3] and may explain this scattering.

MECHANICAL STUDY

Measurement of the Shutter Movement

The rotational movement of the blade has been measured with a dedicated set-up. One part of the valve body, a blade and its rotation axis have been manufactured for this purpose. A rotation sensor directly linked to the blade axis is used to measure the kinematic parameters. The evolution of the angle during the closure is given in Fig. 3.

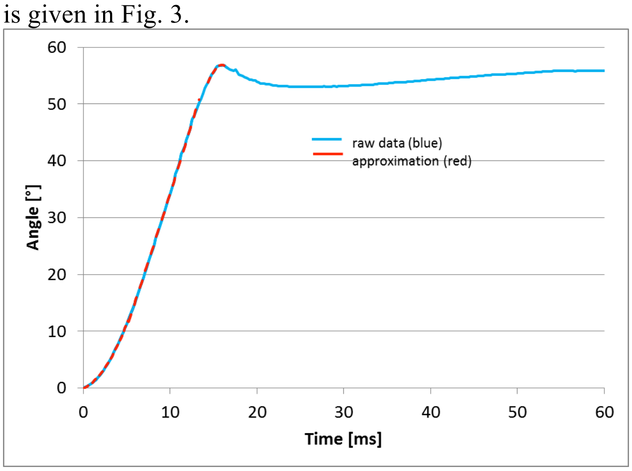

Figure 3 Measures and approximation of the angle as a function of time during the closing.

The results confirm a closing time of around 16 ms. A small rebound is observed. The movement can be split into 4 different phases:

- Constant acceleration
- Constant speed
- Constant deceleration
- Rebound

The maximum rotation speed, acceleration and deceleration are ω=87 rad/s, γ_a=11100 rad/s^2 and γ_d=42375 rad/s^2, respectively. This corresponds for the disc to a radial and orthoradial acceleration of 900 and 5000 m/s^2, respectively. The velocity of the disc center is around 10.3 m/s.

Mechanical Properties of Glassy Carbon

Some mechanical properties of the glassy carbon have been measured at CERN and have been compared to those provided by the manufacturer. 4 point bending tests have been carried out on 5 small plates, 70mm*13mm, 2 mm thick. Strain gauges have been glued on 2 of them.

The elastic mechanical parameters, namely the Young's modulus and the Poisson's coefficient, and the flexural strength are reported in Table 1.

The results confirm the output of one 1D tensile test on grade K, for which a Young modulus of 27 GPa and a Poisson's coefficient of 0.17 have been estimated. These Young modulus measurements are quite close to the manufacturer data (35 GPa). It is worth to note the dispersion obtained for the flexural strength. They are probably due to small chips observed after the sample cutting, even with diamond wire. The measurements around 120 MPa are significantly lower than the manufacturer data (260 MPa, depending on the grade). This may be explained by the sample preparation and also by the different geometry of the specimens.

Table 1: Measures of the Elastic Properties of Glassy Carbon

	Young Modulus [GPa]	Poisson's Coefficient	Flexural strength [MPa]
Grade G	32.4 ±0.8	0.155	112 ±10
Grade K	32.5 ±1	0.17	120 ±12

Deflection Under Vacuum

The deflection of a glassy carbon disc has been measured under vacuum and compared to the estimations. Theoretical deflection for simply supported or clamped disc under uniform pression, p, are given by:

$$\delta_s = \frac{3}{4}\left(1-\nu^2\right)\frac{pR^4}{Et^2} \quad (1)$$

$$\delta_c = \frac{3}{16}\left(1-\nu^2\right)\frac{pR^4}{Et^2} \quad (2)$$

with t and R the thickness and radius of the plate. E and ν stand for the Young modulus and the Poisson's coefficient.

A finite element analysis has been carried out including the fillet radius for the contact between the disc and its support. Different axial gaps between the disc and the upstream guide have also been taken into account. The upstream and downstream guides are considered infinitely rigid. The estimations given in Fig. 4 are in quite good agreement with the measurements.

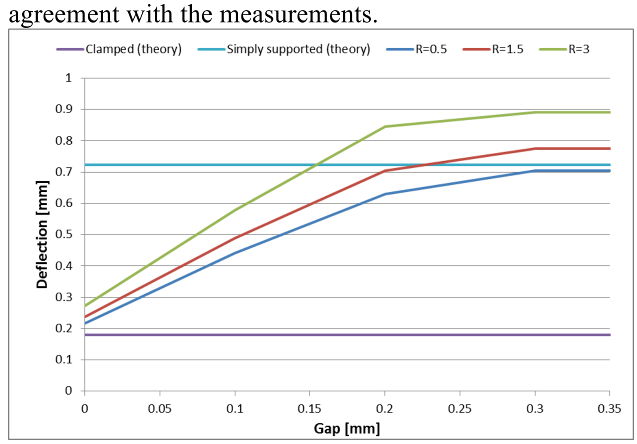

Figure 4: Estimation of the deflection under vacuum for different geometrical parameters.

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For example, a deflection of 0.78 mm has been measured on a simply supported disc for a fillet radius of around 1 mm. For a gap of 0.2 mm, the disc starts to come in contact with the guide at the edge. This has also been observed experimentally.

Test and Simulation of an Overpressure

A rupture test has been carried under pressure. The nominal gap between the disc and the body is 0.2 mm and the fillet radius is around 1.5/2 mm. The rupture has been observed for a relative pressure of 4.3 bar.

In a structural analysis, the stresses are classically compared to the strength of the material giving a safety coefficient with respect to the loads. Failure is obtained when an equivalent stress equals the material strength. For brittle materials, the Rankine theory based on the maximum principle stress criterion is usually used. With this analysis, it turns out that the failure of the disc would be driven by the contact with the support and strongly depends on the fillet radius. The failure would occur for a pressure of around 5.5 bars for a fillet radius of 1.5 mm.

A second approach has been carried out based on Weibull's theory that is more adapted for brittle material. The survival probability reads:

$$P_S^{\Omega} = \exp\left(-\frac{1}{V_0} \int_{\Omega} \left(\frac{\sigma_{eq}}{\sigma_0} \right)^m d\Omega \right) \quad (3)$$

V_0 is commonly considered to be equal to 1 mm^3. σ_0 and m stand therefore to the two material parameters of the Weibull's law, called scale and shape parameter. σ_{eq} represents the equivalent stress and is usually equal, for ceramics, to the positive part of the principal stress. The shape parameter, m, that represents the dispersions, has been estimated to around 6 for a grade of glassy carbon [4]. No data is available for the scale parameters. Nevertheless, it has been defined assuming that the strengths given by the manufacturer corresponds to the average strength to rupture. This analysis tends to show that for a fillet radius of 1.5 mm the failure is driven by the flexural stresses and not the contact local compressive stresses whereas this is the contrary for small fillet radius (0.5 mm for example). This has to be confirmed by additional statistical data on glassy carbon mechanical behaviour.

Dynamic Loads and Fatigue Tests

High dynamic loads develops during the fast blade closure. For an in-plane rotation movement, dynamic specific forces read:

$$\vec{f} = \rho\omega^2 R\vec{e}_r - \rho\frac{\partial\omega}{\partial t} R\vec{e}_\theta \quad (4)$$

where ρ stands for the specific mass, R is the distance between the considered point and the rotation center. ω denotes the rotation speed. A finite element 2-D model has been developed assuming plane stress state. Contact elements are used between the glassy carbon disc and its support in titanium. A static analysis is carried out considering the dynamic forces as load. In the worst case, the maximal principal stress in the disc is around 30 MPa in compression and few MPa in tension. The maximum Von Mises stress in the support is around 30 MPa. The valve has been subjected to more than 200 closure/opening cycles. No damage has been observed on the blade.

CONCLUSION

A fast valve based on a pendulum motion of a glassy carbon disc has been studied. The valve body and actuator have been provided by VAT.

The glassy carbon material, heat treated at 3000 °C, has been validated for UHV applications. The leak rate obtained by direct contact between the disc and the guides depends on the disc surface but is acceptable for the application. The material exhibits sufficient strength so that the disc withstands the atmospheric differential pressure. A reliability analysis with respect to differential pressure has been carried out. Nevertheless, more material statistic is required to draw a confident conclusion.

The dynamic parameters of the valve have been measured. The closing time of around 16 ms is conformed to manufacturer data. The measurements of the kinematic parameters of the blade have been injected into a FE analysis. It turns out that the dynamic stresses in the disc and its support remains small. The valve has been subjected to around 200 cycles opening/closure without any sign of damage of the blade.

The study of the thermal mechanical behavior of the glassy carbon disc under local heat deposition induced by the interaction with the beam is developed in [5].

As a conclusion, a fast valve employing a glassy carbon disc, that offers high transparency and high temperature strength, has been validated from vacuum and mechanical points of view.

ACKNOWLEDGEMENT

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