DEVELOPMENT OF VACUUM CHAMBERS IN LOW Z MATERIAL

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Abstract

Highly transparent vacuum chambers are increasingly required in high energy particle physics. In particular, vacuum chambers in the experiments should be as transparent as possible to minimize the background to the detectors, whilst also reducing the material activation. Beryllium is, so far, the most performant material for this application, but it presents some drawbacks such as brittleness, manufacturing issues, toxic if broken, high cost and low availability. A development work to obtain an alternative material to beryllium with similar performance is being carried out at CERN. Three categories have been defined and considered: raw bulk material, material composites and structural composites. The main functional requirements are: vacuum compatibility (leak tightness, low outgassing rate), temperature resistance (in the range 200-230 °C), transparency, and mechanical stiffness and strength. After beryllium, carbon is the element with the lowest atomic number that is practical for this application; therefore carbon based materials have been considered in a variety of options. In this paper, several technologies are presented and discussed. Results of preliminary tests on samples are also shown.

INTRODUCTION

Vacuum chamber development in composite material began at CERN in the 1980s [1,2,3]. The motivation for this research has always been to offer a cheaper, more readily available alternative to beryllium vacuum chambers for the experimental areas, whilst maintaining equivalent transparency. Several attempts are recorded in the CERN archives, two examples being carbon fibre chambers that were installed in NA48 and LEP.

The transparency of a vacuum chamber is determined as the ratio thickness over the radiation length, t/X_0, and is therefore optimum for the thinnest chamber with the highest radiation length material. From the mechanical point of view, the failure mode of a thin walled vacuum chamber is usually the buckling. The critical buckling pressure is in the form:

$$P_{cr} \propto E\left(\frac{t}{R}\right)^3$$

where E stands for the Young modulus, t and R denote the thickness and radius, respectively. A figure of merit for the material, considering the transparency and the buckling strength, can therefore be expressed by:

$$X_0 E^{1/3}$$

Table 1 gives this figure of merit for different materials. It is worth to mention that composite stiffness strongly depends on the ply orientation, lay-up and fibre properties. As previously mentioned, after beryllium, carbon is the element with the lowest atomic number that is appropriate for this application; therefore all high carbon content materials, especially composites based on carbon fibre that offer high stiffness and high radiation length, are good candidates.

Table 1: Figure of Merit for Different Material

	Radiation length [cm]	**Young modulus [GPa]**	**$X0E^{1/3}$**
Beryllium	35	290	230
Epoxy	30-36		
CFRE	30	~ 200	175
Carbon	29	35 (GC)	95
Carbon/Al (60/40)	17	120 (short fibers, randomly oriented)	84
SiC	8	450	61.3
Al2O3	7	390	51
SiC/Al (40/60)	8.6	140	45
Al (+Li)	10-11	78	43
Al	9	70	37
Ti	3.7	113	18
316L	1.8	200	10.5

TECHNICAL OPTIONS

Different material technologies have been considered:

1. Raw bulk material: the material is homogeneous and leak tight.
2. Material composite: The material is composed of a matrix reinforced with fibres or particulates. The leak tightness is obtained either by itself or with a coating. Mechanical properties that can be obtained by homogenization theories are given by the composite properties.
3. Structural composite: A thin membrane, likely in aluminium, is used to obtain the leak tightness. It is reinforced to withstand the mechanical loads. The macroscopic behaviour is given by the reinforcement and the aluminium foil.

Raw material

Glassy carbon

Glassy carbon (GC) is obtained by the pyrolysis at high temperature of a highly reticulated resin. Two grades from HTW (Hochtemperatur-Werkstoffe GmbH, Thierhaupten, Germany) have been considered. Grade K is obtained after a heat treatment at 1000 °C whereas 3000 °C is used for the grade G. Chemical analyses have been done by EDS. The material is composed of around 98 % (weight) of carbon and 2% of oxygen.

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The thermal outgassing and the permeation have been measured. It turns out that grade K presents high thermal outgassing, dominated by water whereas grade G has a thermal outgassing of around $2.5.10^{-13}$ $mbar.l.s^{-1}.cm^{-2}$ for hydrogen after a baking at 150 °C for 2 hours. For inner wall impedance and vacuum performance reasons, aluminium and NEG coatings are being tested.

The main issue of this material lies in its brittleness and the difficulty to join a glassy carbon part with a standard metallic interface flange. Brazing tests have been carried out and were encouraging. In addition, development of carbon nanotube reinforcement is on-going with the manufacturer.

Aluminium alloy

The aluminium alloys remain a good backup solution since their manufacturing processes and characteristics are known and/or manageable. New grades with lithium are now available (series 2000) or in development (series 5000). The addition of lithium tends to increase the Young modulus and the transparency. Mechanical and welding tests are on-going to qualify the available grades.

Composite material

Carbon fibre/ aluminium matrix

Long carbon fibre reinforced aluminium matrix composite has initially been developed for aerospace applications [4] and light weight structures [5]. The composite is obtained by gas pressure infiltration of liquid aluminium in a carbon fibre preform. The galvanic coupling between aluminium and carbon is an issue in a saline environment but probably not in normal conditions in an accelerator or experiment [6]. In addition, titanium coating on the fibres can prevent this effect. Some samples have been provided by Thales Alenia Space and Dresden University. First leak tests and thermal outgassing measurements have shown good and promising vacuum performance [7].

Nevertheless, this material is not widely commercially available. An alternative with short fibres has been proposed. It could be obtained by powder technology and could ease the manufacturing process. This would lead to a reduction of the mechanical properties but an estimation based on a Mori Tanaka homogenisation still shows the interest of this solution (table 1).

Carbon fiber reinforced epoxy + aluminium coating

Sample pieces of carbon fibre reinforced resin of 100x100x2 mm were coated by PVD. These samples were supplied by QinetiQ (UK). Coatings of Aluminium, Silicone and Titanium were applied. Coating thicknesses ranged from 100 to 500 nm. When carrying out leak tests on these samples, all items started with a background between 10^{-9} and 10^{-10} mbar.l/s and rose to between 10^{-7} and 10^{-8} mbar.l/s after several hours [7]. A non-coated sample exhibited similar behaviour. Samples have since been coated by another method (Hipims) and are awaiting results. First impressions are that single layer coatings, no matter how controlled the environment, will always have small leaks. This would be coherent with previous studies of coatings on polymers [8] that exhibited pin holes due to the presence of dust. These pin holes led to high thermal outgassing.

Further developments are foreseen. The first one is a multilayer coating with intermediate treatments. They would aim at a redistribution of the dust and therefore of the pin holes between two layers. The second alternative is an electrolytic coating with ionic liquid.

Structural composite

External aluminium membrane + internal reinforcement

Internal reinforcement in C/C (Carbon Fibre Reinforced Carbon) has been studied. The C/C is a composite material obtained through a multi-stage process where a matrix of graphite is reinforced by carbon fibres. Grade SIGRABOND FilWound 2001G, supplied by Steinemann Carbon AG (through SGL Group), has been assessed.

Outgassing tests were made with a Ti external barrier, having obtained a rate of about 1.10^{-12} $mbar.l.s^{-1}.cm^{-2}$ after a bake-out at 250 °C [9], which is compatible with previous tests [10]. Both Al coating, made to fulfil beam impedance requirements [11], and NEG coating were successfully made. Regarding NEG, results are promising. After activating for 6 hours at 250 °C the sample that has a coated surface of around 2500 cm^2, a pumping speed of 500 l/s for H_2 was measured.

Structural analyses are on-going in order to better understand the behaviour of the set-up. The main aim is foreseeing and controlling the behaviour of the aluminium membrane to optimize its thickness. The critical point is the differential thermal expansion during the bake out that leads to the buckling of the membrane.

Mechanical and brazing tests are to be started.

Internal aluminium membrane + external reinforcement

Another solution is the external carbon fibre reinforcement of an internal leak tight membrane in aluminium. The interface between the membrane and the resin has to withstand the vacuum force most importantly including during the bake out when higher stresses are generated due to differential thermal expansion. For polymeric resin, no strong covalent bounds occur and creep, especially at high temperature may happen. Ceramic resin or geopolymer [12] are therefore being assessed.

Sandwich structures with an internal aluminium skin are another alternatives. Samples of sandwich structures were supplied by Euro composites. These samples were then heated above 200 °C to test the adhesion of the face layer. It was found that all glues delaminated and therefore no further investigation has been made on this type of structure due to the unreliable nature of the glue bond between layers.

CONCLUSIONS AND PERSPECTIVES

The development of vacuum chambers for UHV applications in a low atomic number material is on-going at CERN. This would offer an alternative to the beryllium, presently used for most of LHC experimental central vacuum chambers. At this stage, different material categories have been defined including the composites, and a wide spectrum of technical solutions based on carbon has been considered. All solutions require additional study and development to be extend to a real vacuum chamber. After the choice of the best candidates, an intermediate step with the manufacturing of small prototypes will be done. This will allow qualification from both a mechanical and vacuum point of view.

REFERENCES

[1] C. Hauviller, Development of composite tubes for experimental vacuum chambers of colliders, EPAC 1988, p. 1143.
[2] O. Grobner, C. Hauviller, LEP vacuum chambers for experimental regions: experience with the first generation, prospects for the second generation, EPAC 1990, p. 1326.
[3] G. Engelmann, M. Genet, and W. Wahl, Vacuum chambers in composite material, J. Vac. Sci. Technol. A 5, 2337 (1987).
[4] J. Pora et al. , Elaboration and evaluation of carbon fiber aluminium composites for aerospace applications, Aluminium Alloys, Vol. 3, p. 1867.
[5] W. Hufenbach et al., Study of manufacture of CF/Al-MMC with aid of the gas pressure infiltration method, Composites 10: 3 (2010) 213-217.
[6] S. Payan, Comportement à la corrosion galvanique de matériaux composites à matrice d'alliage d'aluminium renforcée par des fibres de carbone haut-module, PhD thesis, 2001, Université Bordeaux I, France.
[7] A. Charaux, Etude de la faisabilité d'une chambre à vide en matériaux composites, CERN EDMS 1240624.
[8] M. C. Bellachioma, Applicazione di film sottili per il controllo della diffusione e della permeabilità di materiali polimerici per UHV, PhD Thesis 2004, UNIIVERSIITÀ DEGLII STUDII DII PERUGIIA, Italia, CERN-THESIS-2004-060.
[9] G. Schneider, private communication.
[10] J-P. Bojon, D. Le Ngoc. Taux de degazage des graphites, CERN, EDMS 413846.
[11] B. Salvant et al. Impedance studies of a proposed design for a composite beam pipe, CERN, EDMS 1172415.
[12] Davidovits et al., Matériau composite céramique-céramique et procédé d'obtention, Patent EP0288502B1.

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