USE OF SILICON CARBIDE AS BEAM INTERCEPTING DEVICE MATERIAL: TESTS, ISSUES AND NUMERICAL SIMULATIONS

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Abstract

Silicon Carbide (SiC) stands as one of the most promising ceramic material with respect to its thermal shock resistance and mechanical strengths. It has hence been considered as candidate material for the development of higher performance beam intercepting devices at CERN. Its brazing with a metal counterpart has been tested and characterized by means of microstructural and ultrasound techniques. Despite the positive results, its use has to be evaluated with care, due to the strong evidence in literature of large and permanent volumetric expansion, called swelling, under the effect of neutron and ion irradiation. This may cause premature and sudden failure, and can be mitigated to some extent by operating at high temperature. For this reason limited information is available for irradiation below 100°C, which is the typical temperature of interest for beam intercepting devices like dumps or collimators. This paper describes the brazing campaign carried out at CERN, the results, and the theoretical and numerical approach used to characterize the extent of the swelling phenomenon with radiation, as well as the p+ irradiation test program to be conducted in the next future.

INTRODUCTION

In the continuous search for novel materials to be used as energy absorbers for the core of beam intercepting devices, particular attention is being put on Ceramics [1]. In the frame of the LIU-PSB Project at CERN [2], several preliminary studies, for the application of ceramics to the internal dump for the new H- injection, have been carried out. Particular consideration has been finally given to Silicon Carbide (SiC), since it has been identified as the only material capable to address all the requirements while dealing with the pulsed heat load of the beam [3]. In this context, a SiC-to-metal brazing was also foreseen to be necessary, as mechanical support and to allow the evacuation of the deposited heat.

In this paper, tests and numerical simulations carried out and still on-going at CERN on (α)SiC are described.

METAL-TO-SiC BRAZING

Methods

Although ceramic joining technologies have been studied since the 1940s, metal-to-ceramic joining is much less developed and its use at high stress levels is rather limited [4]. Considerable research and industrial efforts have been pursued during the last decade, also driven by

the interest of the nuclear industry in the use of SiC as cladding material, but very little information is released upon this kind of very complex, and often copyrighted processes. Brazing of SiC to various metals has been tested in the past with promising results [5], while in 2009 CERN has tested several sizes of OFE Copper-to-SiC brazing which resulted in evident cracking [6].

The success of such brazing depends on many parameters [7,8]. Of primary importance is the similarity of coefficient of thermal expansion (CTE) for the two materials, while the brazing alloy should absorb any differential contraction leaving limited residual stress at the end of the thermal cycle [9]. To this purpose, the brazing alloy must guarantee very good wetting onto both materials, but also it should be chosen with regard to its CTE, ductility, and strength.

Recently a second testing campaign has been launched at CERN, aiming for the brazing of SiC Ekasic G and T types from ESK [10] to TZM alloy [11]. Molybdenum was indeed proposed as SiC brazing counterparts based on the functional need of a high-Z material behind the absorbing core, but above all because of the very similar CTE of these two materials in the temperature range of interest. Moreover, TZM allows high strength and creep resistance, which are advantages for our application.

Preliminary tests were carried out to select the brazing alloy based on its reactivity and wetting upon the two counterparts, as well as to adjust the thermal cycle and the pressure applied on the brazing surfaces. These pre-tests allowed us fixing an optimum set of brazing parameters.

Results

The vacuum brazing campaign has been performed on both SiC types and on three different surface sizes, corresponding to 1/8, 1/4 and 1-to-1 scale of the final application (2840 mm^2), and by interposing a 50mm-thick Cusil-ABA® film [12] in between of the two surfaces (Figure 1). The brazing surfaces were both required to be cleaned and with a maximum roughness of Ra 0.8 and a shape tolerance within 0.02mm. The following thermal cycle was applied on the pressed assembly:

- 150°C/h warm-up to 765°C followed by 1h30 dwell
- 200°C/h warm-up to 840°C, and 6 minutes dwell
- 50°C/h cool-down to 700°C
- 100°C/h cool-down to 200°C

This was followed by the switch-off of the oven and final smooth cooling to ambient temperature.

The first microscopic qualitative assessment of the brazing with the final parameter set evidenced some superficial micro-fractures, but in general the overall brazing appeared to be of good quality. The presence of micro-cracks only on the biggest samples suggests that

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we started reaching the limit of CTE admissible difference (in relation to the surface size). Anyhow this cracks only occurred where the brazing material eventually overflowed on the SiC side, and this could be avoided with further optimization of the size of the filler material sheet with respect to the brazing surface size and by improving the alignment between the pieces.
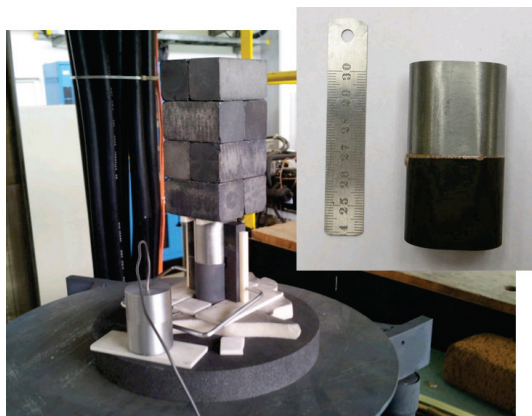

Figure 1: Installation for the vacuum brazing of TZM-SiC specimens and a brazed specimen (top right).

Further ultrasonic testing evidenced the very good quality of 7 brazing over 8 (Figure 2), while one of them, on the biggest specimen size, showed a very scarce wetting of the brazing surfaces, which could be imputed to erroneous setting of the brazing parameters.
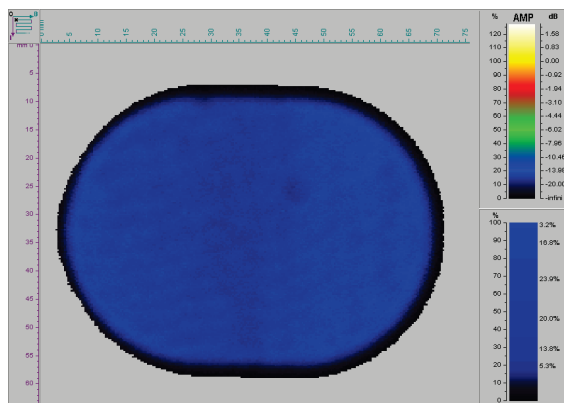

Figure 2: Result of the ultrasonic test of a 2840mm^2 TZM-SiC brazed specimen.

The chosen brazing alloy has a thermal conductivity of 180 W/m^{2}K and it is very thin. Its presence should then have very little influence on the thermal flux passing through the brazing, if compared with the thickness and the thermal conductivities of SiC G and T types (110 and 75 W/m^{2}K respectively) and of TZM alloy (146 W/m^{2}K). Any influence on the thermal flux could only come from a bad thermal contact conductance (TCC) of the two brazing interfaces, revealing the presence of a bad brazing.

A series of tests were therefore performed on the smaller specimens for the assessment of the TCC of the

brazed interface. These tests did not show any additional thermal resistance and very high TCC, between 54 and 143 kW/m^{2}K, have been measured, revealing the very good thermal contact and, again, the good quality of the brazing.

Finally, tests have been launched recently to assess the flexural strength of the TZM-SiC brazed joints.

SWELLING IN SiC

Radiation Dose and Swelling

Despite SiC has very good thermo-mechanical properties and that it is often referred to as radiation-resistant material, there is strong evidence in literature of a phenomenon called swelling, a local, temperature-dependant and permanent volumetric expansion which is due to the effect of neutron and ion irradiation.

To different extent this phenomenon occurs to any material, but in SiC it might be large already at very low doses, when working at relatively low temperatures [13,14]. This fact is very important for the design of beam intercepting devices because they often are designed to work at low temperature, for very long time and with high doses, without or with minimum human intervention.

The accumulated dose in the dump core being unevenly distributed, this permanent expansion creates a distortion that grows in time and, on fragile materials such as Ceramics, might causes the premature and sudden failure of the component [15]. An evident solution is the planning of a certain amount of preventive maintenance, if this could be envisaged, based on a partly stochastic failure model. This needs, anyhow, a very good knowledge of the swelling phenomenon, of the component operating parameters (dose, temperature, etc..) and of the material strength itself.

The Strengths of the chosen SiC types are known from the supplier, but the Weibull failure parameters are being tested to further improve this knowledge. On the other hand very limited information is available on radiation induced swelling build-up below ~100°C for (α)SiC, which is the typical temperature of interest for our application. Literature reports this temperature range to be the worse in terms of swelling for (β)SiC [14,16] due to the absence of any temperature-related annealing processes. A literature-based numerical model has been built and exploited while specific tests have been launched.

Swelling Model

For the particular energy spectra of our case study, the dose of 1Gy corresponds to ~ 1E9 1MeV-n-eq and 1dpa to ~ 1E21 n/cm2 [17]. At a given operating temperature T and dose rate d', the swelling amount for (β)SiC, in %, has been found proportional to the power of the ionizing radiation dose d absorbed by the material, measured in DPA [16,18]. This empirical relation is written as:

$$S = \frac{\Delta V}{V} = f(T, d') \cdot d^n \qquad (1)$$

where f = 5.61 for a temperature of ~100 C and a dose rate d' of 1E-3 DPA/s, and n = 0.81.

To enable the numerical modelling of this phenomenon in a FEM code, the dependence swelling strain – dose $\epsilon_S = \epsilon_S(d)$ can be correlated to the more common dependence thermal strain – temperature $\epsilon_T = \alpha \cdot \Delta T$ where α is the material CTE. The only difference here is that the former is a permanent phenomenon. We then assume for the former a correlation of the type:

$$\epsilon_S = \alpha_S \cdot d \qquad (2)$$

where ϵ_S is the swelling strain, α_S is the coefficient of permanent swelling expansion and d is the absorbed dose measured in DPA. Knowing that swelling is a volumetric expansion and hence $\epsilon_S = 1/3 \cdot S$ in a perfectly isotropic assumption, it results from (1) and (2) that this coefficient α_S, measured in DPA^{-1}, can be written as function of the dose (as well as α is temperature dependent):

$$\alpha_S = \frac{1}{3} \cdot f \cdot d^{n-1} \qquad (3)$$

The swelling strains ϵ_S and consequent stresses can then be calculated in ANSYS© by introducing α_S as a fictitious CTE in a quasi-static transient analysis where the temperature field is substituted by the DPA field.

Results

Figure 3 shows the situation inside the dump core, in terms of DPA distribution and DPA peak and in terms of stresses, after 10 years of nominal operation, without adding any thermal load but only considering the swelling strains build-up. As it can be seen, in this low temperature regime a peak dose of less than 0.3 DPA is already causing stresses far above the tensile limit of the material.
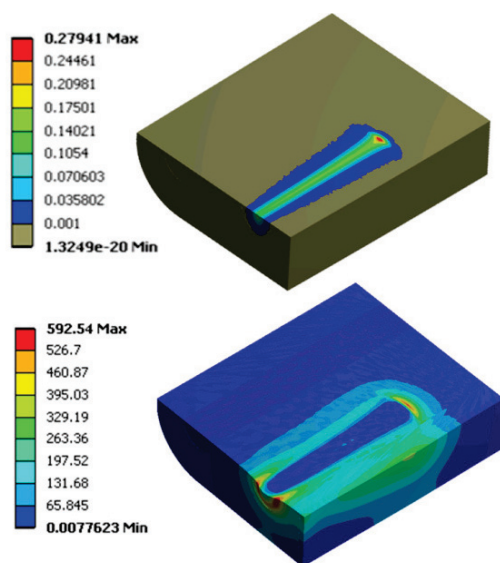

Figure 3: Unevenly distributed dose field (DPA, top) and equivalent Stassi tensile stress field (MPa, bottom) due to only to swelling in the dump after 10 years of operation.

Future Irradiation Tests

The swelling model presented relies upon several assumptions and on the literature-based analytical model described by equation (1). Irradiation tests on (α)SiC samples are being planned in the CERN PS Booster dump region, which will allow to tune the numerical model and build a confident maintenance plan, specifically at the foreseen operational temperature and dose rate.

CONCLUSION

In this paper the TZM-SiC vacuum-brazing campaign carried out at CERN and its results have been described, as well as the theoretical and numerical models used to characterize the extent of the radiation-induced swelling in SiC at low temperature. As a consequence it was possible to draw a preliminary maintenance plan for the SiC version of this internal dump. New tests are now being planned to increase the understanding of this phenomenon and ameliorate the dump maintenance plan.

ACKNOWLEDGMENT

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