# Characterization of Chinese Beryllium as the Candidate Armor Material of ITER First Wall

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**Abstract.** Beryllium has been selected as the armor material of ITER first wall blankets and only S-65C beryllium was regarded as the reference material up to now. Since China and Russia will share the manufacturing of ITER-FW panels, ITER grade beryllium has being developed in both countries. Due to the policy of ITER international organization (IO), candidate ITER materials must be qualified to satisfy the requirements of ITER. As to beryllium materials, an equivalent performance to S-65C beryllium is crucial. In order to demonstrate the damage behaviors of different beryllium grades under ITER operation conditions, two Be/CuCrZr mockups were prepared by means of hot isostatic press (HIP) in which Chinese beryllium, Russian beryllium and S-65C beryllium are included. The Be/CuCrZr mockups were exposed to a high energetic electron beam in the electron beam facility JUDITH-1 at Forschungszentrum Juelich to simulate the transient wall loads resulted from plasma disruption, ELMs and vertical displacement vents (VDEs), as well as the thermal fatigue caused by the normal cycling operation of ITER. In this paper, the manufacturing processes and main thermo-mechanical properties of Chinese beryllium are briefly introduced, and qualification test results of the Be/CuCrZr mockups are presented. The results indicate that an equivalent performance of Chinese beryllium to S-65C under high heat loading has been identified, and it also means Chinese beryllium will be accepted as the armor materials of ITER first wall blankets.

## 1. Introduction

Beryllium was considered as the armor material of ITER first wall blankets owing to its perfect compatible with fusion plasma. Since 2004, vacuum hot pressed (VHP) beryllium was developed in China, aiming at the requirements of ITER because China will share the manufacture task of ITER first wall blankets. After several years' efforts, one kind of VHP beryllium named as CN-G01 was developed. Preliminary characterization of Chinese beryllium was finished at 2008 [1] and its fundamental physical and thermo-mechanical properties satisfied the requirements of ITER, for example, BeO content was very close to 1 wt. % and total elongation rate was in the range of 2.5-3 % at room temperature. However, its thermal shock resistance capabilities was not satisfied compared with S-65C, therefore a modification of the fabrication technique of VHP beryllium was carried out, the fabrication technology was optimized and specified, a lower BeO content and higher elongation rate were reached. According to the acceptance standard of new materials for ITER application, Chinese beryllium was fully characterized and a series of high heat load tests were performed together with a candidate Russia beryllium TGP-56 (with BeO content of 1 and 1.3 %, respectively) and reference beryllium S-65C in an electron beam facility JUDITH-1 (FZJ, Germany) for comparison. This paper will briefly introduce the fabrication procedure and fundamental thermo-mechanical properties of Chinese beryllium CN-G01, and address the results of HHF qualification tests.

## 2. Experimental

### 2.1. Fabrication processes of Chinese beryllium

Chinese beryllium CN-G01 was manufactured by powder metallurgy (PM) vacuum hot press (VHP) process, similar to S-65C beryllium. Firstly, beryllium pebbles with purity of 99% were fabricated from beryllium mineral, then casted into beryllium ingots in a vacuum induction furnace. The ingot surface was cut off and the remainder ingot was mechanically chipped into small pieces, which were then impacted into beryllium powders by high speed gas steam. After classifying and chemical cleaning, beryllium powders for vacuum hot press were obtained. VHP beryllium block was sintered in a hot press furnace at a temperature of 1130-1190°C and a pressure of more than 10 MPa. Meanwhile the vacuum degree of the furnace chamber was kept in the range of $10^{-2}$ -$10^{-3}$Pa. Finally beryllium plates were produced by cutting VHP beryllium blocks along the pressing direction.

### 2.2. Main thermo-mechanical properties of Chinese beryllium

According to the requirements of ITER-IO, Chinese VHP beryllium was fully characterized, and its main properties (at room temperature) are as follows:
Density: 1.83-1.84 g/cm$^3$.
Average grain size: 7-16 μm.
BeO content: < 1 wt. %.
Ultimate tensile strength: ≥ 340 MPa.
Yield strength: ≥ 210 MPa.
Total elongation rate: ≥ 3%.
Thermal conductivity: ≥ 150 W/m.K.
The thermo-mechanical properties at elevated temperature were also measured. The results indicated that the physical and thermo-mechanical properties of Chinese VHP beryllium fully satisfied the requirements of ITER and were very close to S-65C beryllium [1].

### 2.3. HHF qualification tests

High heat load performance is the crucial evaluation criterion of beryllium as plasma facing materials. As the first step of qualification tests, thermal shock tests were carried out to obtain the threshold of crack initiation, which will be used as the parameters of the formal qualification tests. The single shot experiments indicated that cracking initiated at about 2

$MJ/m^2$ and melting then started at approximately 3 $MJ/m^2$ under the load condition of 5 ms pulse duration and load area of 5×5 $mm^2$ [2].

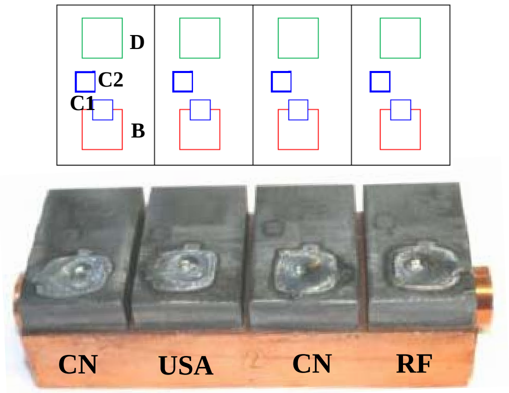

*Fig.1 qualification tests of Be/CuCrZr mockups*

Qualification tests were carried out by using Be/CuCrZr mockups in the dimensions of 42×104×30 $mm^3$ on which different loading conditions can be applied synthetically. Each mockup has 4 beryllium tiles of 40×24×10 $mm^3$, of which two beryllium tiles are CN-Be and the others are RF-Be (TGP-56-1%BeO) and S-65C, respectively. A cooling tube of 15 mm in diameter was embedded in the CuCrZr alloy base as shown in the lower picture of Fig.1. Totally 4 mockups (two Chinese mockups and two Russian mockups) will be tested and the qualification testing program was shown in the upper drawing of Fig.1. Firstly the integrity of every mockup will be checked by a thermal mapping test at a moderate heat flux of approximately 0.5 $MW/m^2$ (step A), then one of the Chinese mockups will suffer the individual heat loads in sequence as follows: step B-VDE simulation as shown in Fig.1, in which red region of 10×10 $mm^2$ will be exposed to a heat flux of 40 $MJ/m^2$ by one shot, here the pulse duration is 260 ms, including 100 ms ramp up and down time, and 160 ms dwell time; Step C-thermal shock tests in which two different area of 5×5 $mm^2$ will receive a transient heat load of 3 $MJ/m^2$ energy density and 5 ms pulse duration (region C1 and C2 as shown in Fig.1); Step D-repetitive tests of 1000 cycles at 2 $MJ/m^2$ heat flux and 25 ms pulse duration, corresponding to the green region D of Fig.1. In addition, besides the transient loads mentioned above, the other mockup will suffer to an additional thermal fatigue testing at 2 $MW/m^2$ for 15 seconds heating and 15 seconds cooling and totally 1000 cycles (step E). Same testing procedure will also be used for Russian mockups.

## 3. Results and discussions

### 3.1. Thermal shock tests by multiple shots

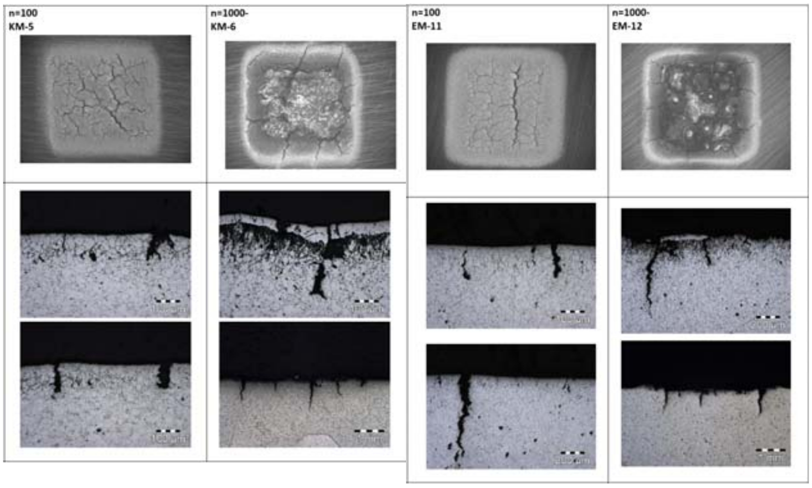

*Fig.2 CN-G01 (left) and S-65C (right) individual samples after 100 and 1000 shots at a heat flux of 1.5 $MJ/m^2$*

Previous thermal shock tests of Chinese beryllium and reference grade beryllium S-65C by single shot did not show any difference and the cracking initiated at an energy density of about 2$MJ/m^2$ [2]. However, the situation changed for the case of multiple shots, for example, after 100 shots at

1.5 MJ/m$^2$ absorbed energy density, obvious cracking was found for both beryllium grades and the surface damage became serious with shot number increase as shown in Fig. 2. Cracking even initiated at lower energy density with the increase of shot number. This should be taken into account in the engineering design of plasma facing components since the repeated transient heat load could occur at the same position.

### 3.2. Qualification tests

Formal qualification tests were performed on four Be/Cu mockups, two of them were supplied by Russia by means of brazing technology and the beryllium surface finished by chemical etching, the others were supplied by China by means of hot isostatic press and beryllium surface finished by mechanical polishing. Possible heat load conditions under ITER operation environment, such as plasma disruption, VDE and thermal fatigue, were simulated. The experimental results were summarized as follows:

#### 3.2.1. VDE tests

A heat flux of 40 MJ/m$^2$ with 260 ms pulse duration was loaded on the red region of 10×10 mm$^2$ area in beryllium tiles as shown in Fig.1. After all tests finished, surface morphology and

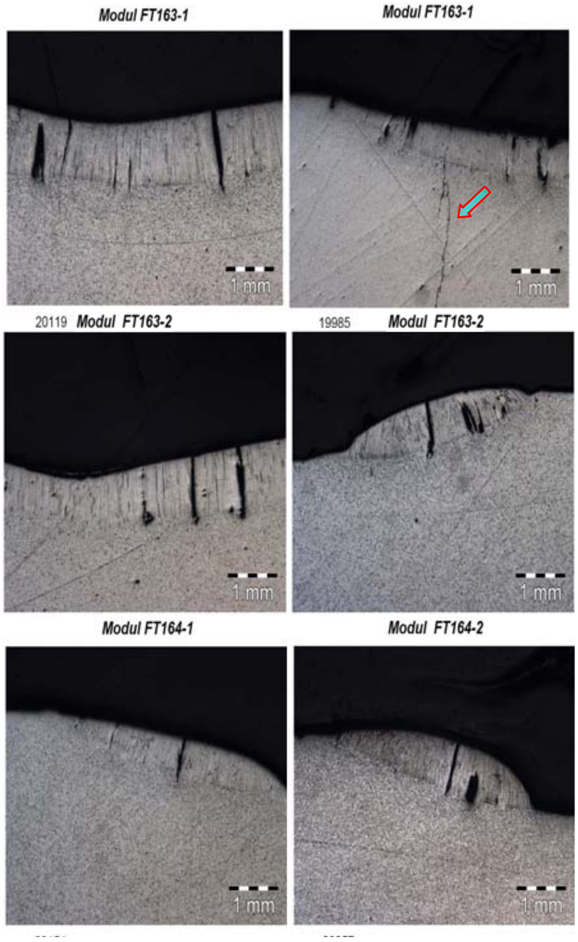

*Fig.3 Metallography observations of CN beryllium tiles after VDE loading*

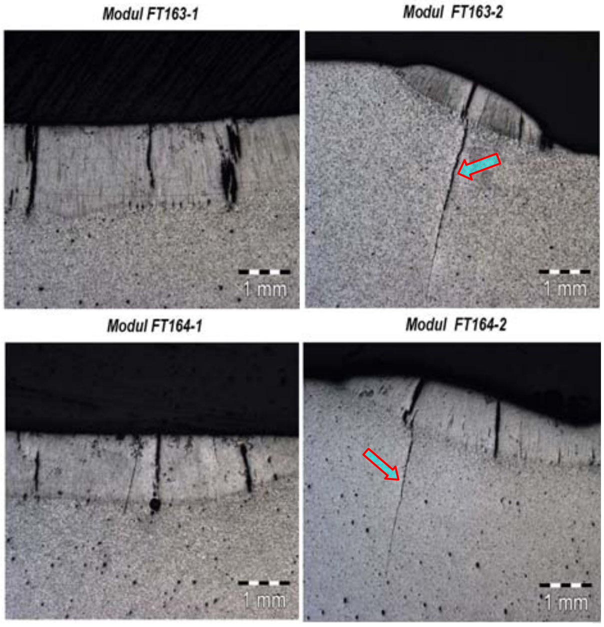

*Fig.4 Metallography observations of S-65C beryllium tiles both in CN and RF mockups after VDE loading*

metallographic observation of all tested beryllium tiles were executed, totally six CN-G01 tiles and four S-65C tiles were tested, their metallography pictures were shown in Fig. 3 and Fig. 4, respectively. Here module FT 163 denoted Chinese mockups and module FT 164 denoted the mockups prepared by Russia, following the number 1 and 2 denoted the mockups tested by the processes of A-B-C-D and A-B-C-D-E, respectively, for example, module FT 163-2 indicated this Chinese Be/Cu mockup will suffer thermal screening (step A), VDE (step B), thermal shock (step C), repetitive tests (step D) and thermal fatigue (step D) tests.

In most cases of Chinese beryllium the cracks ended at the melting layer, only one case was an exception, which is the case of tile 4 in CN-mockup FT163-1, in which a narrow crack with length of more than 2 mm extended into the inner of material. However, such phenomenon similarly appeared in the cases of S-65C, deep cracks propagating into the inner of materials were found in two of 4 tested tiles (Fig. 4). The advantage of S-65C as the reference material of ITER first wall is that cracks induced by severe pulse loading (such as VDEs) usually stop at the re-crystallization layer and are vertical to the beryllium surface, thus avoiding the possibility of beryllium block flaking off [3, 4]. Although the crack propagation commonly happened at the case of beryllium tiles experienced thermal fatigue test, it is uncertain whether the crack extending was caused by thermal fatigue test. Nevertheless an equivalent performance of CN beryllium to S-65C under VDE loading can be foreseen.

### 3.2.2. Transient loads

The load regions are corresponding to the blue areas in Fig. 1, there are two load regions on every beryllium tiles, one is located on the virgin area (C2) and the other overlapped with VDE loading region (C1) with the purpose to investigate the damage behaviors of transient load on different surface structure since a re-crystallization layer will be formed after VDE loading. After thermal shock tests of step C, a lot of surface cracks were found on the loading area of beryllium surface, however, all those cracks did not extend into the deep inner, usually with a depth of less than 100 $\mu$m. A typical cracking behavior on virgin area and the heat-affected region by VDE was shown in Fig. 5. No obvious difference was found for the two cases.

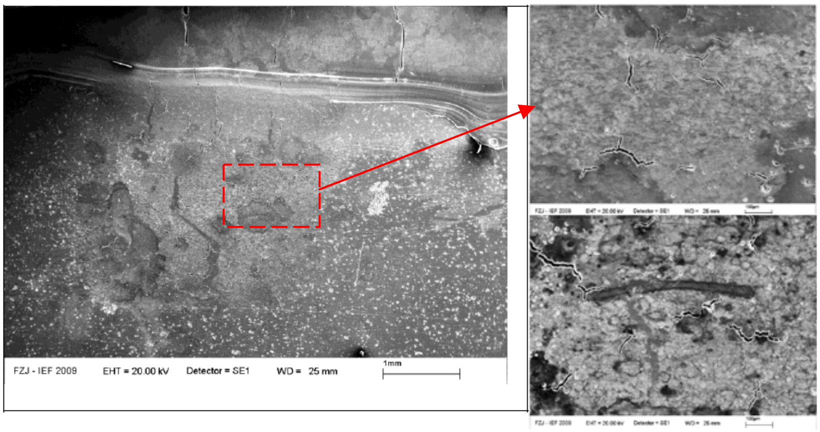

*Fig. 5, Surface damage of beryllium tiles after one shot at a transient heat flux of 3MJ/m$^2$. Left picture shows the load area overlapped with VDE load region and the lower picture at right side shows the case of virgin area*

### 3.2.3. Repetitive tests

This test corresponds to step D in Fig. 1 and is very similar to the experiment made by Watson more than 10 years ago [5], therefore it is so called “Watson” test. Original “Watson” test is a low cycle thermal fatigue experiment by using a spot heat load of 250 MW/m$^2$ for 20 ms pulse duration and repeated once every second (at 1 Hz repeated frequency), in an attempt to find an easy way to rank the relative resistance to crack initiation and propagation of different beryllium grades, and help select the best beryllium for ITER plasma facing materials. Generally “Watson” test carried out in the present experiment did not induce the formation of significant cracking for most cases of CN beryllium tiles. Totally 6 CN beryllium tiles were tested by “Watson” like load and only two tiles indicated somewhat deviations where a relatively long crack appeared in the samples, in particular in the case of CN mockup FT163-1 as shown in Fig. 6. A similar cracking was also found in one tile of S-65C located in Russian mockup FT164-2. According to the previous “Watson” test, crack initiation of S-65C beryllium usually occurred at shot number of more than 1500, the present deviation was finally attributed to a faulty load on this beryllium tile since a pulse heat flux of 3MJ/m$^2$ (same as step C) was falsely loaded on the same region, however, what reason induce the formation of relatively long cracks in CN-G01 beryllium tiles, does it result from different way of surface finishing or material itself? The former seems reasonable since mechanical polish was used for Chinese beryllium tiles and obvious machining nicks can be observed on beryllium surface of Chinese Be/CuCrZr mockups, which could be the crack initiation resource. In order to clarify the cracking reason, an additional “Watson” test was carried out by using individual beryllium samples with dimensions of 12×12×5 mm$^3$, totally 9 samples were tested in which every beryllium grade has three samples, all of the samples were carefully polished by mechanical way in FZJ, Juelich. The experimental results indicated that all testing beryllium grades behaved very similar, only small cracks with a depth of about 30 μm were found. In fact, the damage layer of beryllium surface after machining and roughly mechanical polish commonly has a thickness of about 300 μm, which usually shows the twin-grain structure. Carefully mechanical polish can reduce the thickness of the damage layer, but 30 μm thickness is the minimal. Therefore the micro-cracks can be attributed to the mechanical polish. In addition, it also suggested that chemical etch may be the best way of surface finishing.

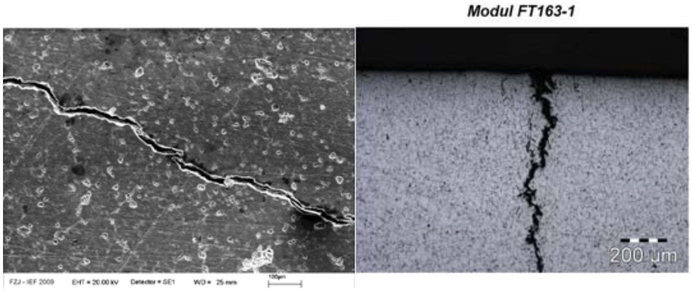

*Fig. 6 Surface and cross section images of Chinese beryllium tile after 1000 pulse loads of 2MJ/m$^2$, 25ms*

## 4. Conclusions

A kind of VHP beryllium (CN-G01) has been developed in China, according to the specification of ITER grade beryllium, CN-G01 was fully characterized and all of its physical, thermo-mechanical properties satisfied the requirements of ITER grade beryllium. Qualification tests of candidate CN-G01 and Russia beryllium TGP-56 was performed in an electron beam heat load facility JUDITH-1 (FZJ, Juelich, Germany) together with reference beryllium S-65C (USA), this qualification test was carried out by using actively cooling Be/CuCrZr mockups and simulated the different load conditions of ITER first wall, such as ELMs, VDEs and thermal fatigue, a repetitive pulse load test similar to that done by Watson was also carried out. Up to now all those tests have been finished and an equivalent performance of CN-G01 beryllium to S-65C has been identified. The final acceptance of Chinese beryllium for the armor materials of ITER first wall is on going and we hope to make a contribution to the selection of ITER first wall materials.

Based on the high heat load experiments of VHP beryllium, the crucial factors influencing the thermal shock and thermal fatigue resistance capabilities of beryllium are its BeO content and plasticity (elongate rate). Furthermore, the method of surface finishing may play an important role for its high heat load performance, chemical etching could be the best way of surface finishing since it can effectively remove the damage surface induced by machining.

## 5. Acknowledgement

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