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Features of plasma sprayed beryllium armor for the ITER first wall

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Abstract

Two water-cooled mockups with CuCrZr heat sinks and plasma sprayed beryllium (PS Be) armor, 5 and 10 mm thick respectively, were fabricated at Los Alamos National Laboratory and thermally cycled at Sandia at 1 and 2 MW/m^2. The castellated surface of the CuCrZr mechanically locked the armor. The resulting PS Be morphology controlled cracking during thermal cycling. Post test examinations showed transverse cracks perpendicular to the surface of the armor that would relieve thermal stresses but not degrade heat transfer. The mockups and two others previously produced for the European Fusion Development Agreement had somewhat porous armor, with a thermal conductivity estimated to be about 1/4 that of fully dense beryllium, due to the low (600–650 °C) substrate temperature during deposition specifically requested by EFDA to avoid subsequent heat treating of CuCrZr. Some melting of the armor was expected and observed in the tests.

1. Introduction

Beryllium (Be) is a comparatively benign impurity in fusion plasmas, and its use as armor on the walls of fusion reactors has attracted interest for many years. The properties of various grades of Be and product forms differ and understanding what grades and properties are acceptable for applications in magnetic fusion has been an active area of research as has the joining of this relatively low melting metallic armor to an underlying structural wall or heat sink [1]. Plasma sprayed Be (PS Be) armor is being evaluated as an alternative to solid Be tiles.

A successful PS Be process both produces the armor and bonds it to even a curved or uneven substrate in one process. Also, plasma spraying is a possible repair technique to mitigate both the time and cost of replacement for a component with surface damage. The development of a mature application for PS Be faces various technical challenges and implies a substantial development program [2]. There has been some significant progress [1–5] but space here does not permit a review. Much of the

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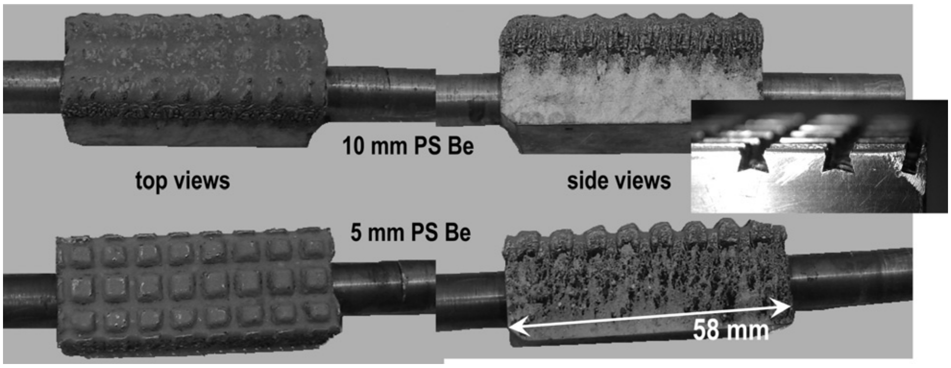

Fig. 1. LANL mockups with castellated substrate and 5 or 10 mm PS Be armor.

work has been summarized in a series of topical workshops on beryllium.[2]

This paper presents the results of high heat flux testing and post test examination of two mockups, each with PS Be on a water-cooled Cu–0.65Cr–0.1Zr (CuCrZr) heat sink, made by Los Alamos National Laboratory (LANL) at their Beryllium Plasma Spray Facility and tested and examined at Sandia National Laboratories. A nearly identical set of mockups was fabricated by LANL for EFDA (European Fusion Development Agreement) and tested with the JUDITH electron beam facility at Forschungszentrum Juelich, Germany.

2. Approach

Cracking of Be armor is an anticipated result of thermal cycling under high heat loads unless the armor is divided into small units (tiles or castellations) to relieve thermal stresses. The mockups tested at Sandia and the EFDA mockups had an innovative feature. LANL researchers castellated the underlying CuCrZr (Fig. 1) so that the subsequent PS Be armor would have both a positive mechanical interlock with the CuCrZr and a morphology that would produce a preferred pattern for cracking perpendicular to the top armor surface. The perpendicular cracking would be beneficial because there would be little detrimental effect on conduction of heat to the heat sink and therefore essentially no degradation of thermal performance. Ref. [4] gives an extensive description of the procedure for preparing the mockups, the morphology of PS Be armor and examination of the EFDA mockups, including metallurgical cross sections.

The principle objective in the thermal cycling tests at Sandia was to observe the pattern of cracking that resulted from thermal cycling tests with absorbed heat loads of 1 MW/m^2 and then 2 MW/m^2. The thermal response of the mockups (surface temperature versus heat load) was characterized first and then each mockup was subjected to thermal cycling tests. The reported temperatures are from a two color pyrometer. The mockups were monitored with two spot pyrometers, an IR camera and a video camera during testing. The mockups each had two embedded thermocouples with the tips just below the castellated region of the CuCrZr. The absorbed heat flux was calculated by dividing absorbed power, measured with water calorimetry, by the heated area on a mockup. The water flow was 10 m/s at 1.0 MPa and 16–20 °C.

In its request to LANL, EFDA specified the following important features: 5 and 10 mm thick Be coating on 22 mm × 58 mm long by 19 mm high CuCrZr alloy to withstand high heat flux, Cu alloy temperature below 650 °C to maintain strength (prevent over aging), minimal post-spray machining (none if possible), and no intermediate layers between the Cu alloy and the Be coating. The mockups for the Sandia test were made to the same specifications as those for EFDA except for the undercut shape of the castellations in the CuCrZr, as opposed to the square shape for the EFDA mockups.

The typical powder composition was 0.64 wt% BeO, 0.086 wt% C, 1090 ppm Fe, 425 ppm Al, 325 ppm Si, bal. Be with a particle size distribution of $-90 + 5$ µm, O-30 gas atomized powder. The surface temperature of the substrate during spraying was 600–650 °C for the 5 mm and the 10 mm coat-

[2] Seventh IEA Int. Workshop on Beryllium Technology, 29 November–2 December 2005, Santa Barbara CA US. Prior workshops were held in Karlsruhe, Germany (1993) Jackson, WY US (1995), Mito, Japan (1997), Karlsruhe, Germany (1999), Moscow, Russia (2001) and Miyazaki, Japan (2003).

ings with transferred arc cleaning of the CuCrZr prior to deposition and transferred arc cleaning during the deposition. The typical torch current was 550 A with 50 standard liters per minute Ar–4%H_2 and a standoff distance of 95 mm. Development and process optimization were not a part of the production of the EFDA mockups, which had, as will be shown, a thermal conductivity estimated to be about 25% that of S65C grade beryllium.

3. Results

Sandia researchers tested the mockups in the Electron Beam Test Stand (EBTS) [6] in January of 2005. The high heat flux tests began with a thermal response test of each mockup. Then thermal cycling tests were done. After these tests, the surface conditions of the mockups were examined in a JEOL 6300 scanning electron microscope (SEM) with particular attention to any cracks that had formed.

3.1. High heat flux tests

The initial thermal response tests obtained curves of surface temperature versus absorbed heat flux. At 1 MW/m^2 the surface temperatures were 165 and 290 °C respectively for mockups with the 5 mm and 10 mm PS Be armor. Fig. 2 shows the results for the 10 mm mockup.

In thermal cycling with the heat flux on for 10 s and off for 10 s, the mockup with 5 mm PS Be armor survived 1000 cycles at 1 MW/m^2 with a surface temperature of ~200 °C. Prior to thermal cycling at 2 MW/m^2, thermal response tests were performed up to 2.5 MW/m^2, and there was some apparent damage at 2.5 MW/m^2. During the subsequent thermal cycling, the surface temperature ratcheted up and the test was terminated at 370 cycles. The mockup with 10 mm armor survived 856 cycles at 1 MW/m^2. The 22×58 mm armored surface of the mockup remained undamaged during this test, but a piece of PS Be at the end of this mockup became overheated and the test was halted. Fig. 3 shows the surface temperature in these tests.

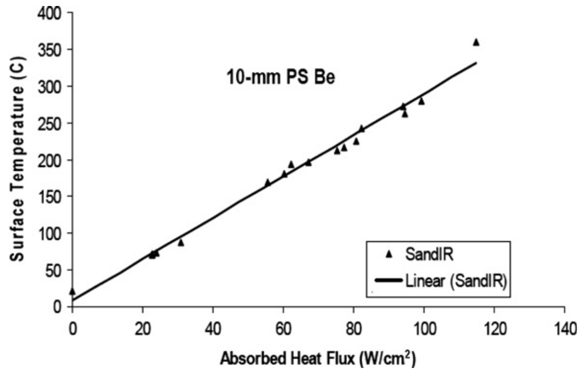

Fig. 2. Results of thermal performance test for mockup with 10 mm PS Be armor.

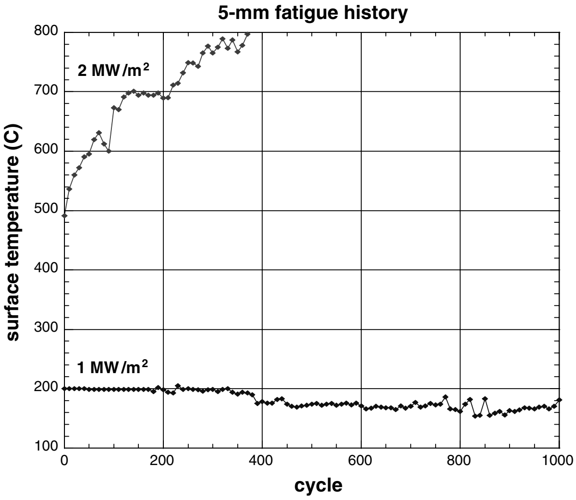

Fig. 3. Surface temperature vs. time for tests of the mockup with 5 mm PS BE armor at 1 and 2 MW/m^2.

For the EFDA mockups tested in the JUDITH e-beam facility at FZJ, Germany, the mockup with 5 mm PS Be armor deposited onto the square CuCrZr castellations survived 1000 cycles at 3 MW/m^2 and the mockup with 10 mm armor survived 1000 cycles at 1.5 MW/m^2.

3.2. Thermal modeling

A simple 2-D thermal model of the mockup with 10-mm armor was created using PATRAN[3] for mesh generation and ABAQUS[4] as the solver. Fig. 4 shows a sample result. Temperature-dependent materials properties were used. The conductivity of the PS Be was varied parametrically as a simple fraction of the value for Be S65-C. The modeling results suggest that the actual thermal conduc-

[3] PATRAN is a finite element code by MacNeill Schwindler Corp (MSC).

[4] ABAQUS is a general purpose finite element code by Hibbitt, Karlsson & Sorensen, Inc. (HKS).

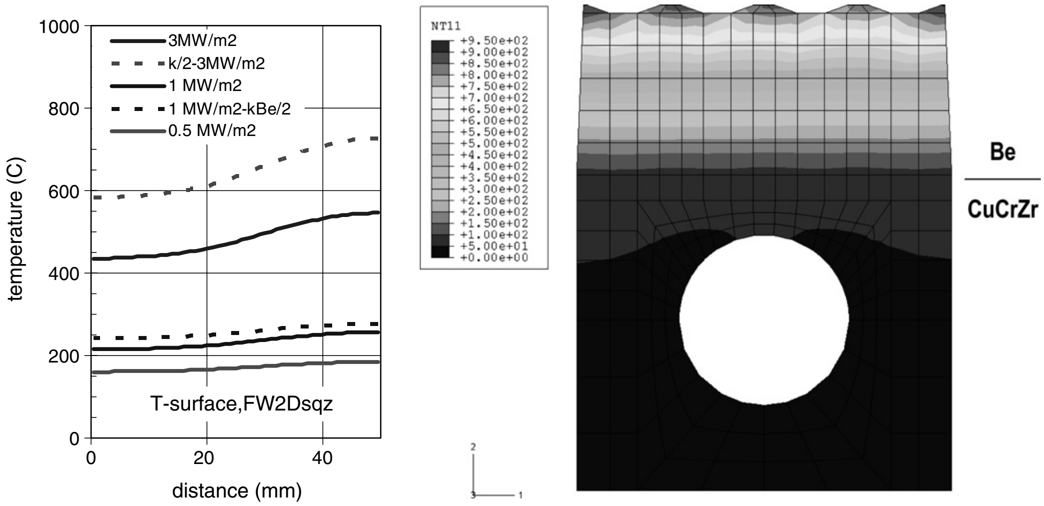

Fig. 4. Results of thermal model.

tivity of the PS Be armor was about 1/4 that of fully dense Be.

3.3. SEM post test examination

Post test examinations were performed with a JEOL JSM-6300 Scanning Electron Microscope (SEM) with an Oxford Instruments Link ISIS Energy Dispersive X-ray Microanalysis System. The basic objective of the post test SEM examination was to note evidence of changes in the surface morphology, including melting or cracking of the Be armor.

Fig. 5 shows composite photos of the crack that runs along the base of the PS Be pedestals in the mockup with 5 mm PS Be armor. Two such transverse cracks were found. In a systematic scanning, no obvious longitudinal cracks were seen. No obvious cracks were found in the mockup with 10 mm PS Be armor.

Melted regions are also evident in Fig. 5. During the testing in EBTS, bright spots appeared and disappeared at various locations in the valleys between the pedestals. These were assumed to be small melted droplets from the pedestals that rolled into the valleys and subsequently evaporated. However, the SEM examination did not reveal any obviously resolidified material in these valleys, and some melting during the transferred arc cleaning of the deposited surface was also likely.

With the 10 mm-thick PS Be armor, the mounds overlying the castellations are more rounded than with the 5 mm-thick PS Be armor. The tops of most but not all of the pedestals on the 10 mm-thick PS Be armor had some melting. Fig. 6 shows an example of the melting.

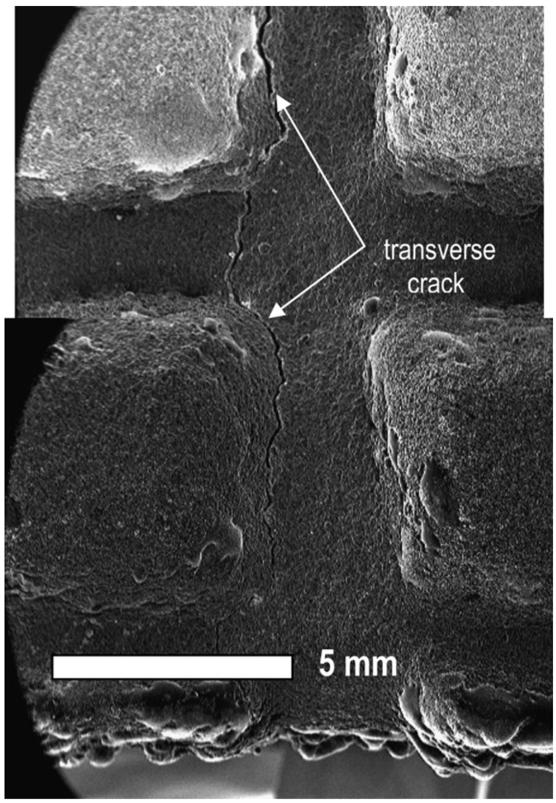

Fig. 5. Transverse crack and melted regions in mockup with 5-mm PS Be armor.

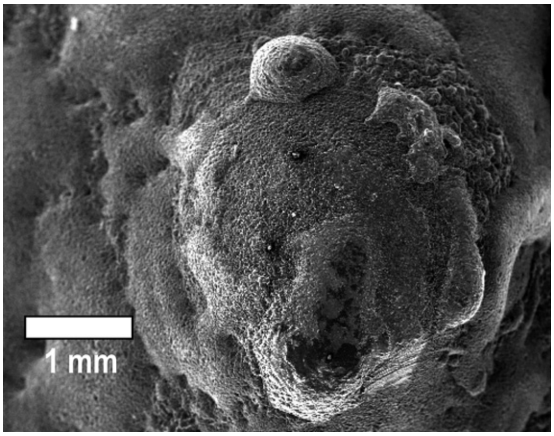

Fig. 6. Melted regions on pedestal on mockup with 10-mm PS Be armor. (15X).

4. Discussion

LANL prepared mockups with PS Be armor using a novel 3-D castellation of the CuCrZr substrate to control cracking in the armor during thermal cycling. The primary finding in these tests was that this approach appears promising based on the crack patterns observed after thermal cycling tests at Sandia. Ref. [4] gives more description of the procedure for preparing the mockups and the results of the high heat flux tests at Judith and at Sandia.

LANL produced the mockups with the relatively low substrate temperatures specified by the customer (EFDA) but without any development process to optimize the technique for these conditions. The relatively low density and thermal conductivity, estimated to be ~1/4 that of S65-C grade Be based on thermal modeling and the observed temperatures in the testing, were not a surprise. Temperature and oxygen content are known to be important factors in the technology of plasma spraying, which has been developed mostly through trial and error. A temperature of 850–1150 °C typically is needed to cause significant sintering in a time of 10–60 min for plasma spraying of beryllium. The exact sintering effects are a function of the starting coating structure and impurity content. For PS Be with a density of 98% that of S65-C grade Be, thermal diffusivity of 94% and bond strength of 184 MPa (mechanical and metallurgical) has been obtained with a substrate temperature of 1000 °C. A density of 90%, thermal diffusivity of 67% that of S65-C and bond strength of 113 MPa (mechanical) has been obtained at 650 °C [5] but with a higher hydrogen gas flow than is now permitted in the new LANL facility. The characteristics of the PS Be armor in these mockups should not be viewed as representative of what could be produced with further development of plasma spraying techniques for this specific application at relatively low substrate temperature.

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