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Beryllium Plasma Facing Components: JET Experience

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ABSTRACT

JET has accumulated practical experience of plasma operation in both limiter and divertor configurations using massive Beryllium plasma facing components. These latter have shown evidence, even after a very short operational phase, for localised melting of the Beryllium surface. Sustained melting results in substantial transport of the liquid Beryllium metal; there is, however, no evidence for low cycle thermal fatigue under this extreme environment. Design has proceeded by analysis largely in support of test bed thermal testing of prototypes. For flux densities ≤ 5 MW/m^2, T surface ≤ 1000 ^oC, typically 200 pulses can be sustained with plastic deformation and no surface fatigue cracking. The latter is seen for more extreme conditions, ie flux densities in excess of 14 MW/m^2, surface temperature > 700 ^oC. Failure of thin claddings of beryllium to heat sinks tend to occur along the beryllium to substrate interface not due to thermal fatigue of the bulk Beryllium material.

1. INTRODUCTION

JET, the Joint European Torus, is the principal experiment on controlled thermonuclear fusion funded by EURATOM. Initial plasma operation in 1983 occurred with a nickel-alloy first wall and fine-grained graphite limiters. Since then there have been three phases of operation of JET, during all of which plasma behaviour has been studied, e.g. [1], in the presence of plasma facing components (PFC) made out of Beryllium:

(1) (design basis) operation with limiter equilibria, e.g. [2].

(2) operation with X-point equilibria generated by the external coil package, i.e. the initial divertor phase, e.g.[3].

(3) the present pumped divertor phase of operation, equilibria generated by additional internal coils added in 1990-1992, i.e. the pumped divertor phase, e.g. [4].

Extensive preparations done by JET to ensure safe access to the interior of the vacuum vessel, as well as handling of (potentially dusty and slightly radioactive) Beryllium components have been described in a companion paper in this issue,[5]. Plasma behaviour with Beryllium PFC's, which has led to it being considered for the plasma facing components of ITER, is described in another paper in this issue, [6].

JET operation using solid Beryllium PFC's, all of which are inertially cooled, has shown that these components retain mechanical integrity under normal and upset conditions. Localised melting along edges during normal plasma operation, sustained melting in the ITER related experiments, has not led to gross mechanical failure of the Beryllium parts.

Micro-cracking of re-solidified zones has been found either due to transient events, i.e. ELM's and disruptions, e.g.[7], or under sustained loading of exposed vertical edges. Cracks appear to be confined to re-solidified areas of components. These patterns differ substantially from fatigue cracking observed under test-bed conditions, e.g. [8,9]. This paper reviews and compares these results with what is seen to predominate for plasma exposure of inertially-cooled solid Beryllium components in JET. Interpretation of test-bed observations by numerical simulation is difficult due to the incomplete nature of the material database for most grades of Beryllium relevant to fusion applications, e.g. [10,11].

The design of the Beryllium-clad ITER first wall and components in selected areas of the divertor region has relied on JET experience and simplified numerical analyses, e.g.[12]. JET observations on low-cycle fatigue of Beryllium clad components has not demonstrated substantial impact of castellation geometry for claddings, i.e.[13,14] in contrast to what is observed for inertial components. This requires further investigation to reduce impact of castellations in future design.

2. BERYLLIUM PFC'S IN JET

Three different types of Beryllium component that have been studied by JET, including studies commissioned by JET to assess prototypical designs. The amounts and grades of material used are:

(a) Belt-limiter tiles, approx. 2 tons, fabricated to near net shape by a (JET-developed) HIP, sinter and cold-pressing process, based on S65b powder; castellations and plasma-facing surface machined after fabrication.

(b) Tiles for dump plates, i.e. for JET X-point configurations using external magnetic field coils only, manufactured by standard HIP process out of S65c powder.

(c) Target tiles for Mark I JET pumped divertor configuration (magnetic field coils inside of the vacuum vessel), near net shape by HIP / extrusion process, machining of several faces (precise seating requirements and plasma facing shape + castellation).

Inertially cooled solid Beryllium target plates and limiters have been used in all three phases of operation. A study prior to 1992 restart of plasma operations was made of cladding water-cooled heat sinks with thin plates of Beryllium material for potential JET applications. Despite intensive testing and development, the option of actively cooled target plates clad with Beryllium (or with carbon fibre reinforced carbon) for the present phase of JET operation was rejected. Thus, there is no JET plasma experience on the behaviour of actively cooled (duplex) Beryllium PFC's under tokamak operation.

3. BELT-LIMITER CONFIGURATION

Prior to installation of the first Beryllium PFC's, i.e. the JET Belt Limiter system, [2], several off-site experiments were commissioned by JET. First plasma exposure of a Beryllium limiter occurred in the UNITOR facility,[15]. These limiters were subject to sufficiently low heat fluxes as to avoid melting. The second set of plasma experiments comprised extended operation of ISX-B with Beryllium limiters, [16] in three operational phases:

(a) first phase with low power to avoid melting of the limiter surface;

(b) next phase of neutral beam heated discharges during which power fluxes of up to 40mw/m**2 were admitted for up to 0.3sec;

(c) final phase that began with intentional melting of limiter surfaces, followed by discharges similar to the previous phase of operations.

The ISX-B limiter was designed, after prototypes were tested and evaluated by Sandia National Laboratory (Albuquerque). It was determined that castellations 13 x 13 x 10mm deep showed an adequate fatigue life when irradiated at $25MW/m^2$ for 0.3s, e.g. [8,17] in an electron beam facility. Figure 1 shows three views of the same limiter tiles from ISX-B ie. including sustained surface melting. It is evident that localised melt degrades the very precisely machined surface. Nevertheless adequate plasma operation could be sustained in the presence of damaged tiles, c.f.[16].

Figure 1. Three views of ISX-B Beryllium limiters. Note alternating castellated and uncastellated components. Top view, after initial ohmic operation, no melting evident. Middle view, after neutral beam heated discharges engendered some melting. Bottom view, after substantial edge melting with flux densities up to $40MW/m^2$

The JET belt limiter design concept comprised some 1900 Beryllium tiles positioned so as to present an precisely machined surface to the plasma, c.f [4]. Sandia National Laboratory (Albuquerque) were commissioned to examine fatigue behaviour for 10000 cycles at a nominal flux density of 4 - 5MW/m^2, Tmax at end of pulse < 1000C. Three uncastellated tiles (two 10mm, one 20 mm wide) by 100mm by 65mm deep were found to show runaway thermal fatigue failure. The tiles shown side by side in Figure 2 were subject to 4000 cycles at 4 MW/m^2 in an electron beam irradiation facility.

Figure 2. Sandia National Laboratory tests of JET belt limiter prototypes. After 4000 pulses at 4MW^2, 1000 pulses at 4.5MW/m^2. Electron beam irradiation.

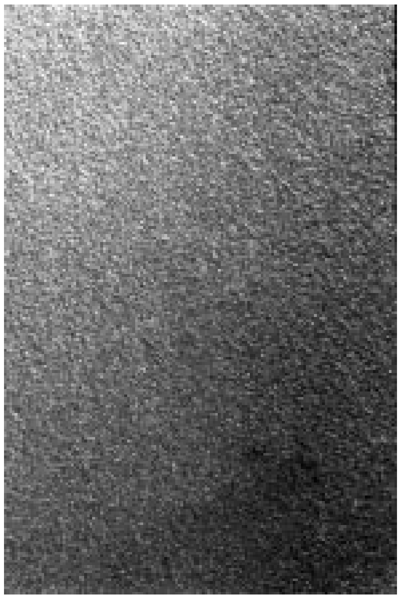
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Figure 3. Sandia National Laboratory tests of JET belt limiter prototypes. Castellated tile, top face view after 300 pulses at 4MW/m^2. Electron beam irradiation.

Castellation of a tile was mandatory in order to sustain test conditions without runaway fatigue cracking. The castellated sample (20x20mm wide, cuts 10mm deep) showed no substantial cracking after 300 cycles, cf. Figure 3. After 10000 pulses, small but visible micro-cracks were found that appeared to be self-limiting into a depth of 2mm, see Figure 4. There were no visible cracks at the root of castellations,[8]. There were, however, cracks lateral to the irradiated surface propagating from the vertical edges of the castellations, cf. Figure 5.

JET operation with Beryllium belt-limiter tiles showed that the principal thermal loading occurred along poloidal edges. Very high localised heat fluxes, estimated ≤100MW/m^2 produced local melting of poloidal corners. The maximal extent of these melted edges correlated with a magnetic field to tile distance variation of up to 2mm (due to field ripple and installation accuracy combined), [19]. A segment of melted castellation of a belt-limiter tile after plasma exposure is shown in Figure 6. Clearly, some cracks are visible in the re-solidified material. The crack direction was found to be parallel to the heat flow direction. Cracks were found also to penetrate into virgin material underlying strongly heated zones of the tile. It is noteworthy that

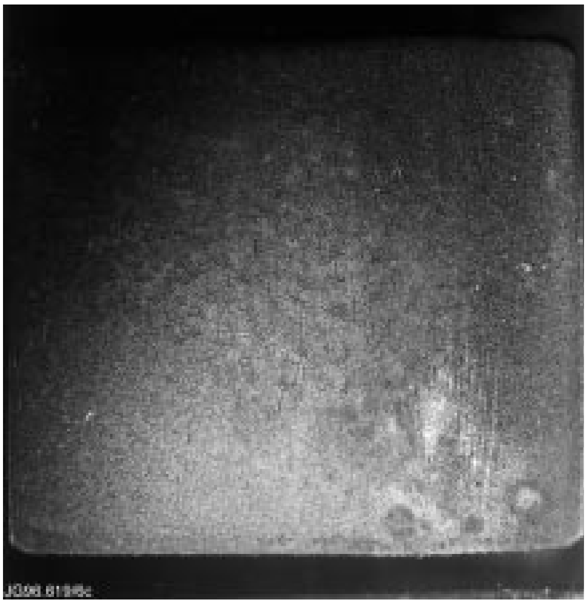

Figure 4. Sandia National Laboratory tests of JET belt limiter prototypes. Castellated tile, top face view after 3600 pulses at 4MW/m^2. Electron beam irradiation.

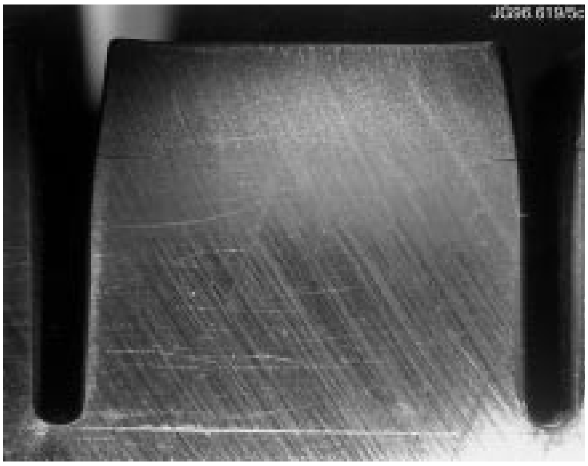

Figure 5. Sandia National Laboratory tests of JET belt limiter prototypes. Castellated tile, edge view after 10000 pulses at 4MW/m^2.

there was no evidence for fatigue cracking at the root of castellations. In total some 3x10^3 castellations were found to have some parts of the surface that were melted or strongly heated without prejudice to the overall integrity of the component.

A first experiment with X-point magnetic configurations used recycled Beryllium RF antennae protection tiles. These tiles, made in an identical fashion to the belt-limiter tiles, had dimensions 10 x 180 x 50(max.) mm high without any castellations. Tiles were specially shaped over the nominal plasma facing edge. Despite localised melting due to re-ionisation of injected neutral beam particles, these tiles showed no thermal fatigue failure in their original positions. In the reused configuration angles of incidence of magnetic field lines were very unfavourable. Gross local melting with liquid layers of several mm depth being regularly formed occurred as can be seen in Figure 7. No gross mechanical failure of thesetiles was observed even with substantial melting of the surface and material loss from the tiles. Power flux densities to the molten areas were estimated at 40 - 100 MW/m^2.

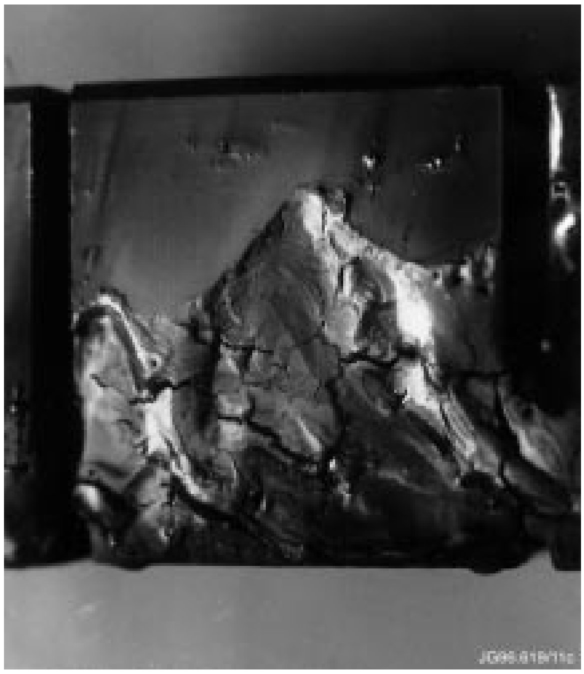

Figure 6. JET belt limiter tiles after plasma operation. Note surface cracking of melted and resolidified areas. Edge flux densities of max. 100MW/m^2, top fluxes of 4-5MW/m^2

The JET belt limiter and RF limiter tiles derived from S65 powder, delivered by Brush Wellman according to Revision b (material specification current at that time). Tiles were produced to near net shape by a combination of sintering and cold pressing. The material was characterised in some detail, c.f. [20,23] and are shown in Table 1 below. Also shown in the table are measured values for Brush Wellman standard product (a HIP process) based on S65 Revision C powder (presently available).

Figure 7. JET RF antennae tiles reused as target plates for X-point operation after plasma irradiation. Note significant material transport of molten material and no global cracking of the uncastellated tile. Initial edge flux densities up to 50MW/m^2.

Table 1: Yield stress (MPa) for selected grades of S65 powder metallurgy based material for JET applications: T, transverse L-longitudinal

Temperature	**S65b (20)**	**S65c (21)**	**S65c (22)**
°C	**T/L**	**T/L**	**T/L**
20	273/270	–	264/261
25	–	251/228	–
100	–	244/229	–
200	234/232	–	–
300	–	231/219	–
370	–	–	176/179
400	177/179	–	–
500	–	144/144	141/147
600	122/119	–	–
649	–	–	76/73

A second type of target for divertor configurations was installed in JET to accommodate X-point discharges after the initial experiments reported above. Studies were made by SNLA of the thermal fatigue characteristics of tiles nominally 100x100x (30 and 40) mm deep. Initial experiments on uncastellated plates showed unacceptable deformation after a few pulses at low power (less than 2.5MW/m^2),[24]. Plates castellated to a geometry of 20x20x10mm deep (for both 30 and 40mm thick plates) were tested under heat fluxes of 2.5MW/m^2 for 20s pulses in the Ion Test-Bed at SNLA.. No fatigue cracking was observed of these components after 1000 cycles: however, substantial global plastic deformation was noted, [23].

The Beryllium dump-plate tiles for JET were carefully shaped to present a precisely aligned surface to incident heat flux. The field lines were at grazing angles of incidence, i.e. <3 degrees, and potentially very close to zero degrees angle of incidence. Under such conditions minute tile irregularities present a nearly vertical surface on which heat fluxes of the order of 300MW/m^2 would impinge. The tiles were nominally 37mm thick, castellated by slits 0.8mm (rounded root of slot) spaced on an approximate scale of 20x23.5 mm. Localised melting, as seen in figure 8 was found to have occurred during normal plasma operations with this target. No gross mechanical failure was observed.

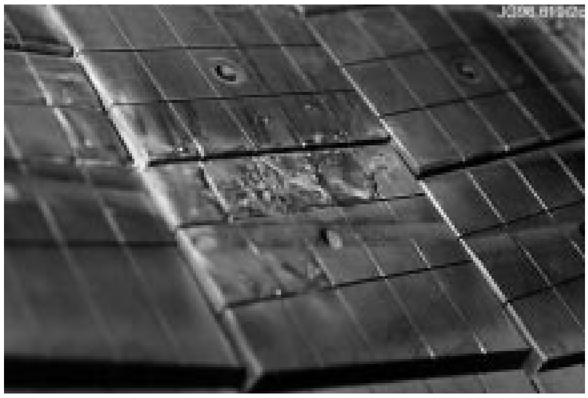

Figure 8. JET dump plate Beryllium tiles used as target plates for X-point operation. Note castellations of 20x23mm, edge melting and some transport of molten material. Vertical exposed edges at 300MW/m^2; shaped faces at <10MW/m^2.

4. MKI TILES - OBSERVATIONS

JET operation in the pumped divertor phase restarted in 1992 using Carbon-fibre reinforced Carbon tiles as target material. The targets were again inertially cooled blocks of material with a fixation technique that allowed enhanced area for radiative and conduction cooling of the tiles between discharges, cf, Figure 9. A limited number of discharges were studied with a full set of Beryllium tiles installed, including the deliberate melting of these tiles to simulate ITER relevant conditions. The Beryllium target tile set was, therefore, allowed to develop melted zones under controlled conditions. The appearance of tiles after the end of these experiments is seen in Figure 10.

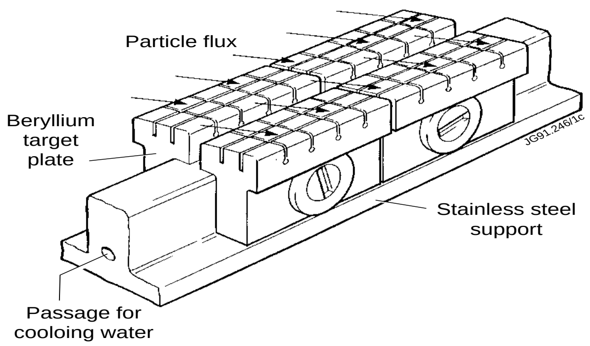

Figure 9. JET Mark I Beryllium target plate concept. The schematic shows a design option of key-hole shaped bottom of slots in one direction. The slots were finalised as 0.8mm wide slits with a 0.2mm 45 degree chamfered flat bottom in both directions.

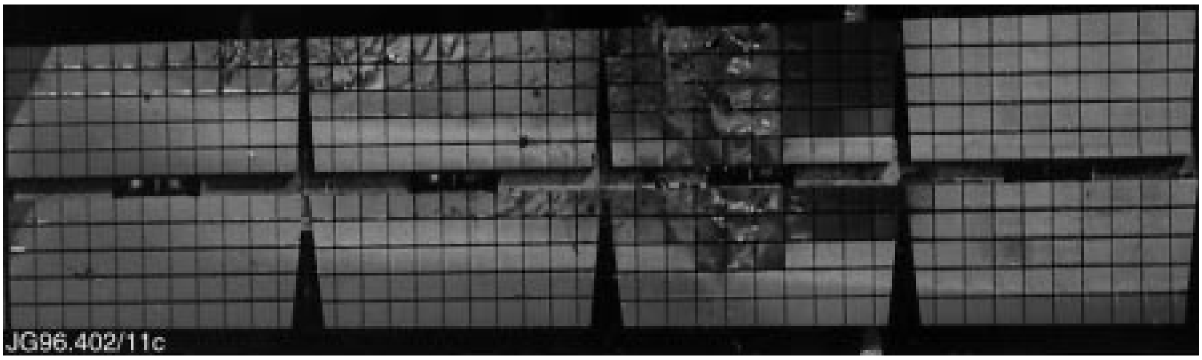

Figure 10. JET Mark I Beryllium target plate tiles after plasma operation. Note localised melting on second tile from left above is due to a single giant ELM crash (1MJ/M^2 over 100 microseconds). Substantial melting of second tile pair form right above is due to ITER dedicated experiments, power flux densities of maximum 20MW/m^2.

The Mark I Beryllium tiles were designed to a very high degree of accuracy. The massive pieces of Beryllium with a T-shape, the stem is a further 30 mm deep. Tile global widths of 30 - 40 mm and a poloidal extent of 79 mm were chosen early in the design process and could not subsequently be altered.

Table 2 Fatigue studies S65c (standard production procedure) material

Castellation lateral extent	Parameters type depth shape	Test data cycles Flux MW/m^2 cycles	Outcome
10 x 14mm	6mm round + round	5-16 6500	cracked and melted
8 x 12mm	12mm round + keyhole	5-16 6500	cracked and melted
6 x 6mm	8mm round + round	5-25 2x10^4	cracked
7 x 7mm	10mm round + round	5-19~2600	safe
5.5 x 6.5mm	8mm round + round	5-19~2800	plastic deformation

A series of thermal fatigue tests were carried out for several castellation geometries, cf. Table 2 above. At flux densities of ~14 MW/m^2 (surface temperature ≤ 1000^{o}C) failure occurred of the large castellations. Cracks propagated vertically downwards into the material, possibly branching laterally at a depth of several mm. Lateral cracks propagated from the edges of the castellation at depths of typically 2 mm. These cracks sufficiently perturbed heat flow that localised surface melting started to appear.

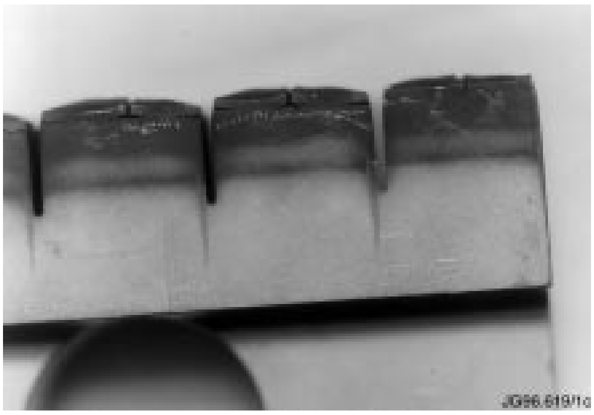

Figure 11. Fatigue testing results of Mark I prototype tile. After cumulative irradiation of approx. 6500 cycles at flux densities up to 19MW/m^2. Irradiation in JET Neutral (hydrogen) Beam Test-Bed. Note substantial cracking of the relatively large castellations, 8x12mm.

Numerical analysis had suggested that the degree of metal plastification was strongly related to the geometry of the root of a castellation. A pair of tiles with key-hole type castellations was tested, cf. Figure 11. Thesurface cracking of these tiles was very similar to that observed for the other set, ie 10 x 14 mm (6 mm deep round slot). Metallographic studies showed no difference, ie no cracks developed in either the round or key hole slots after >6000 stress reversals, [9].

4.1. Mark I Tiles - assessment

The Mark I Beryllium tiles required a high degree of accuracy to maximise power handling. In fact, every castellation presented some edges exposed to very high heat fluxes. These were mitigated by machining the edges of each castellation. There were more than 8000 tiles, with 40 - 50 castellations per tile.

Despite the care taken during fabrication, installation and initial plasma operation, termination of discharges by disruptions or the presence of ELMs resulted in localised melting, see Figure 10. Numerical assessment of the consequences of an ELM was possible in the following ascending degree of difficulty:

(a) energy deposited, derived through closed form relation

(b) temperature rise during an ELM, tyically flux densitites are >300MW/m^2 over <10 microseconds, through 1-d finite element calculations

(c) stresses amd strains in the material underlying the melted region, through 2d and 3d finite element analysis.

The problem of whether a given power loading produces a two-dimensional (plane stress or plane strain) state of transient thermal stress or a truly three dimensional state of stress, had to be considered in the evaluation of the fatigue studies. The simplest approach of carrying out three dimensional analyses for all geometries leads to unacceptably large numerical models. Substructuring in thermal stress problems is notoriously difficult.

The following analysis is offered to give an appreciation of the limits to numerical prediction in terms of assessing the design of a castellated Beryllium PFC of complex shape. To study the limits to castellation, consider the inertial response of a 20mm thick layer of Beryllium. Consider for the moment the simplest zero-order castellation, i.e. a series of Beryllium towers of square section (transverse to the direction of heat flow). The irradiated surface is in compression during the heating phase.

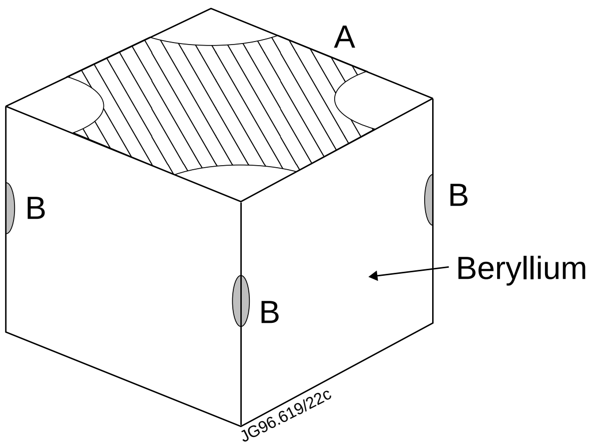

Figure 12. Schematic of regions of maximum plasticity in a 20mm high free standing upright prism of Beryllium.

There is vertical compressive stress over most of the free surfaces adjacent to the irradiated surface but at right angles to it, cf. Figure 12 for a schematic representation of the situation.

Representation of the true stress situation by two-dimensional plane stress analysis recovers many of the qualitative features of the true stress state. However, this approach fails to predict accurately the onset of plastification of selected regions in the model problem. Furthermore, for situations where there are part-thickness castellations, the two-dimensional approach is found to be inadequate. Figure 13 shows schematically the state of stress in a partially castellated inertial block of Beryllium subject to a uniform surface heat flux.

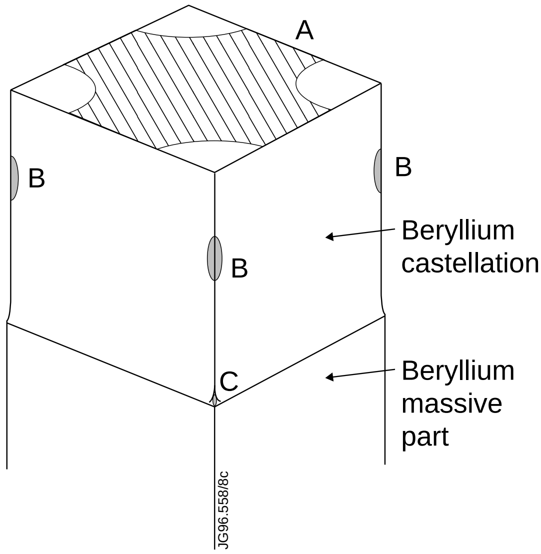

Figure 13. Schematic of regions of maximum stress plasticity in a 20mm high free standing upright prism of Beryllium that has been castellated through part of the total thickness.

The stress level in the upper part of a castellated piece of Beryllium is reduced since the effective width of the piece is equal to the castellation pitch. The depth of a castellation, length of heating pulse and shape of the root of a castellation all determine whether stresses penetrate to the root, ie position C in Figure 13. Typically, JET values of 6 - 8 mm depth give a heating time of ~ 0.25 seconds for the stresses at position C to develop plastic zones. Depending on the flux density plastic zones may develop at all three positions A, B, or C. Experience shows that position B may become critical, ie lead to failure by lateral cracking even for the smallest castellations studied, ie at 20 - 22 MW/m^2 for 6 x 6 x 8 mm deep castellations.

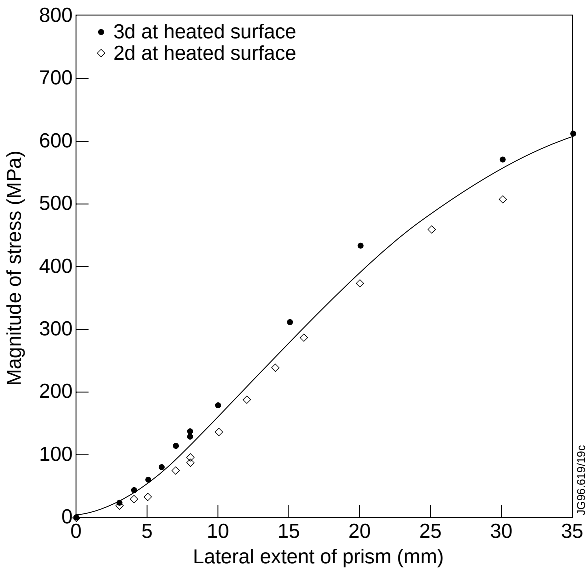

Figure 14. Variation of peak value of lateral stress at the irradiated surface of a 20mm free standing prism of Beryllium: numerical results for 5 second irradiation at 5MW/m^2, two dimensional (plane stress) and three dimensional models analysed. Solid curve indicative of trend with increasing lateral extent. Three dimensional model is, e.g. 6x6mm square in cross-section.

The model problem comprised comparing two-dimensional plane stress and three dimensional results for the positions shown in Figure 12. The ABAQUS [24] finite element programme was used to calculate results. Elastic analysis with temperature dependent thermomechanical properties[20] was carried out suppressing the onset of plasticity. Figure 14 shows a comparison of the lateral stress at the irradiated surface using 2d and 3d analysis. The curve in the figure is indicative of the trend (represents the average values). Several points are to be made.

(1) Both 2d and 3d analyses show the same trend of maximum value of stress tending to increase (essentially without bound) as the lateral dimension increases;

(2) 3d results are generally substantially higher than 2d results for the same geometry; the results plotted in Figure 14 do not have the same mesh size (3d meshes typically 3x 2d meshes due to computational limits);

(3) Other stresses, notably stresses along the edge of a square prism are grossly underestimated in 3d plane stress analyses.

Metallurgical sections have been taken of the strongly melted tiles, cf Figure 9, second tile pair from the right in the photograph. The root of castellations was for financial reasons made to be a flat bottom with two side chamfers, see Figure 15. A stress crack some 2 mm in length was found to occur at the position of maximum stress (cf Figure 13) for a tile subjected to some 10 discharges of surface wading ~ 20 MW/m^2.

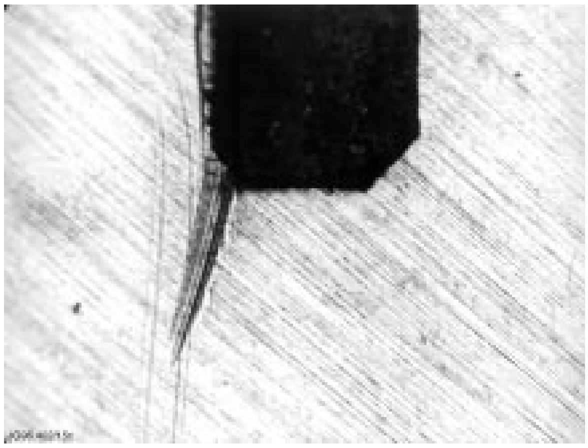

Figure 15. View of damage to root of castellation taken from a Mark I tile in the strongly melted area of the Mark I experiments.

In terms of assessing the thermomechanical response, little data has been published for elevated temperatures. Exceptionally some data is available for S200E up to 1100C. More typically published data is available over the range T<800C, i.e. mostly for S65c. Published data is contradictory for Poissonís ratio and there is no systematic fatigue data available for elevated temperature service. A PFC that sustains localised melting shows very high localised strain rates, up to 100 /sec has been estimated for ELM impact on the JET S65c Mark I tiles, [7].

5 BERYLLIUM CLAD HEAT SINKS

Beryllium-clad water-cooled heat sinks were studied as prototypes for an actively-cooled divertor target for the pumped divertor phase of JET, i.e.[25]. These comprised thin (1 1/2 mm to 3mm) plates of S100F and S100FH material brazed to a Copper Chrome Zirconium substrate, i.e. [26]. In tests a series ofcastellated geometries was studied: 27 x 27 mm plates, 27 x 6 mm plates, 6 x 6mm castellations in 27 x 27 mm plates fully penetrating to the brazed layer, and 6 x 6mm castellations as above through 2/3 of the thickness of a 2 mm plate. Failure by debonding occurred for all of these geometries at flux densities 14 - 16 MW/m^2 [14]. Numerical studies had suggested that 6 x 6 mm castellations would significantly reduce the problem of plastification of the heated surface. This effect, predicted by 2d plane stress calculations, did not appear to be significant for failure.

Testing of thin plates of Beryllium bonded to a water-substrate has shown little evidence for thermal fatigue in the bulk of the Beryllium cladding for 1000 cycles at heat fluxes up to $10MW/m^2$ [14]. Numerical study of this result shows that there is little plastification of the heated zone. In fact, there appears, under the assumption of perfect plastic behaviour of Beryllium post-yield, to occur shake down on essentially the first pulse that reaches steady state. The test sequence comprised short pulses of 1 - 2 seconds of heating; calculations show that under such circumstances after some 10 - 15 pulses shake down would occur at very low plasticity levels near the heated surface, typically ≤ 0.5% for fluxes ≤ 10 MW/m^2 and the JET test conditions. Debonding of the cladding, rather than thermal fatigue, is observed at higher flux densities, typically after several pulses at a flux density of $14\text{-}18MW/m^2$.

Recently, thick (10mm) claddings of S65 Rev c material, brazed to the same type of substrate, have been studied for ITER-relevant conditions up to and including melting of the heated surface,[28,29]. None of the water-cooled clad components studied in the neutral-beam test-bed at the JET site has been exposed to plasma irradiation in the main JET facility.

This observation differs from JET experience with castellations of thick, inertially cooled blocks of Beryllium. It is to be noted that very few measurements have been made of the fatigue of Beryllium-clad actively-cooled components for more than 10^3 stress reversals under ITER relevant flux densities. The present programme of ITER commissioned testing is noted in this regard, [30].

Figure 16 shows a view of the melted and resolidified surface of 10 mm S65c brazed to a CuCr Zr hypervapotron heat sink. Flux densities of 20 - 25 MW/m^2 were applied in an ion beam (neutral + ion beam) dedicated JET test facility such as to allow strong and sustained melting of the surface. Resolidification after heating for 2 - 3 seconds at 20 - 25 MW/m^2 onto the liquid metal produced a surface that was remarkably similar to the original unmelted one [28]. Note, however, low-cycle fatigue cracks that are evident in Figure 16. Detailed micro photographs [29] show that these cracks propagate along the columnar recrystallized Beryllium grains of the strongly heated parts into virgin material below.

Figure 16. Surface melting of 10mm thick tiles (S65c) brazed to CuCrZr heat sink after irradiation at $25MW/m^2$ in the JET Neutral (hydrogen) Beam Test-Bed.

6 SUMMARY

JET has extensively used Beryllium in a variety of solid, inertially cooled components, that have sustained in total, several thousand full power plasma discharges. Typically S65 revision b and c powder has been used with a variety of fabrication techniques. The most recent ITER dedicated experiments have been on components made as S65c vacuum hot pressed material. Thermal fatigue has also been studied under test-bed conditions for a variety of geometries, including thin castellated bonded layers to a heat sink. It is found that the tokamak environment admits more severe localised loading of these PFC's leading to local melting and microcracking of small regions. The large area fatigue failures of loaded surfaces seen under test bed conditions have not been reproduced by PFC exposed to plasma in JET.

JET castellation strategy based upon a combination of analysis and experiment led to a simple rule: castellations of the order 6x6mm by at least 7mm depth to survive 1000 stress reversals for fluxes up to $20MW/m^2$ and no surface melting. Three dimensional analyses are mandatory to interpret the observations of cracking at the root of castellations, which has only been seen cf the requirement of no melting at $20MW/m^2$ was not observed.

The thermal performance of massive or thick claddings of Beryllium under localised overload is difficult to assess numerically . The relevant data for modern grades of Beryllium as published has to be extrapolated to temperatures above 700C. Furthermore, Beryllium is likely to melt and the thermal properties of liquid Beryllium are not widely disseminated.

Lifetime of PFC's, in JET under plasma operation has been determined by global alignment and machining tolerances rather than by high cycle fatigue. Lifetime of cladding is difficult to predict even in absence of melt layer removal since

(i) there is a non-computable singularity at edge of cladding

(ii) low cycle delamination/failure of bond may correlate to ductility of Beryllium in the braze affected region

(iii) plastic behaviour of Beryllium cladding requires extensive modelling to determine shakedown

The summary of JET experience is that a combination of careful design, to mitigate the occurrence of local hot spots, combined with testing of prototypes has produced very robust Beryllium plasma facing components.

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