Mechanical study of JET MKI beryllium tiles after ELMs and deliberate melting

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1. INTRODUCTION

The JET MkI divertor configuration was designed for operation using either CFC or Beryllium as target materials. After an initial CFC phase of operations [1], the entire set of tiles, approximately 7300, was exchanged. The beryllium phase of MkI operation, in early 1995 [1], was carefully scheduled to minimise inadvertent melting of the Be target tiles.

A single giant ELM that appeared near the ELM-free divertor discharge [2] was found to have melted approximately 0.075 m^2 of the Be tiles.

In overloading tiles an experiment done in support of ITER [2], surfaces were subjected to a normal flux density of 20 MW/m^2. IR observations [3] show that the surface temperature rises above melting temperatures over $0.3m^2$ of tile surface.

This paper presents some conclusions on the extent of melting due to the single giant ELM and surveys the mechanical state of resolidified areas of deliberately melted parts. No gross mechanical failure was observed; no fatigue cracks are visible as observed by JET [4,5] and others [5] in test-bed experiments where melting at flux densities up to 25 MW/m^2 was deliberately induced.

2. MATERIAL AND GEOMETRY OF MKI TILES

Melting of MkI Be tiles did occur as a result of ELM's, deliberate overloading, and possibly due to disruptions. Figure 1 shows the cumulative damage to one module of 4 tile rails. The MkI target tiles form a set of 384 tile rows, mounted inpairs on 192 rails. One tile is slightly higher to

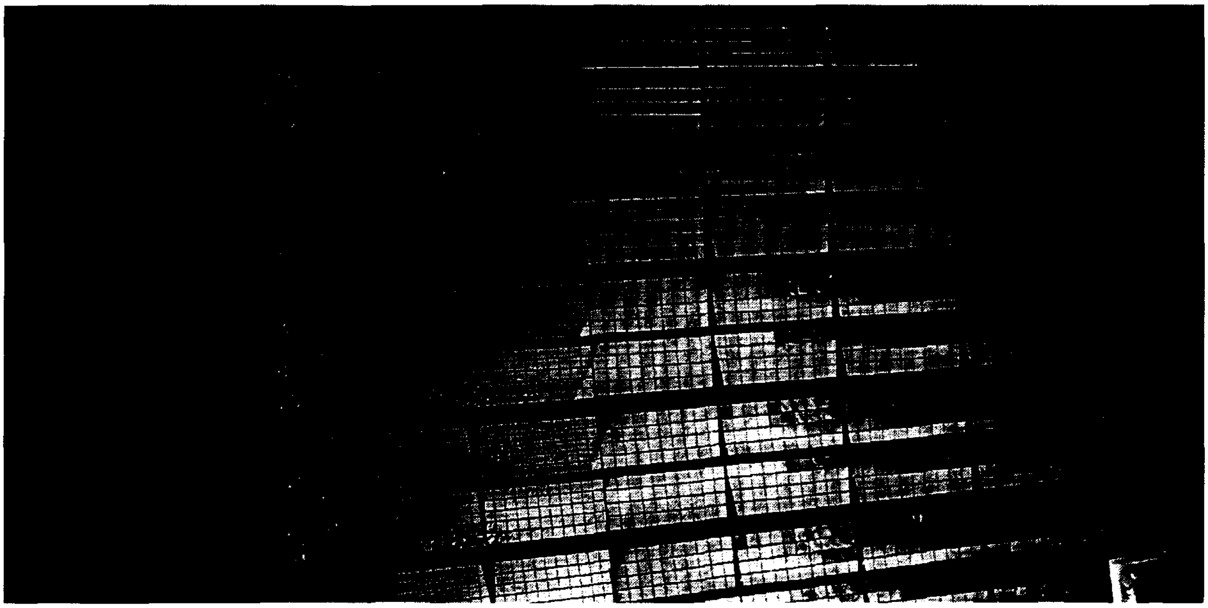

Figure 1. Cumulative damage to MkI Be tiles

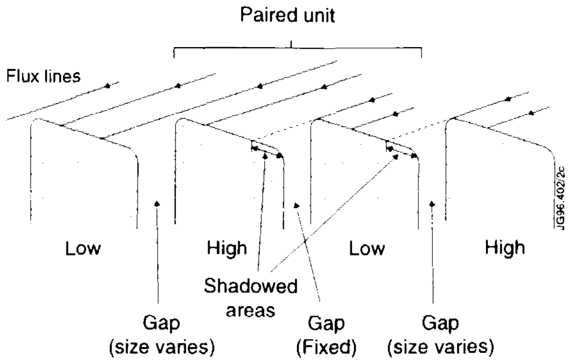

Figure 2. MkI target concept

offset geometry variation, thus tiles have been labelled high and low in figure 2. The high tile is raked at 5.2°, the low tile at 4.2° in the vertical toroidal plane, cf figure 2.

Tile features that determine the melted area for any configuration are (a) relative height of the high and low tile in a tile pair, (b) the tile rail angle in the vertical poloidal plane, (c) the angle of inclination of tiles in the vertical-toridal plane and (d) tile spacing. These values were chosen to handle a range of plasma equilibria. it is noted that at most ~50% of the available area could be melted.

The beryllium tile surface facing plasma flux is castellated in order to improve high-cycle fatigue characteristics. Furthermore consideration of edge exposure produce the raked edge of tiles and the chamfering of the edge of each individual castellation.

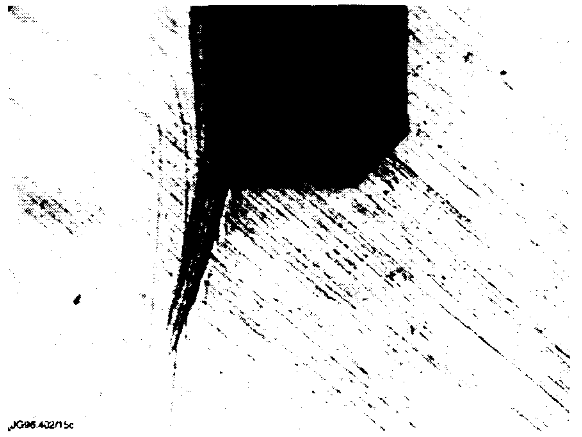

Figure 3. Section of base of castellation

Manufacturing and installation have been identified by JET from its experience to influence the global power handling capabilities. Exposed vertical faces imply power handling reduction by orders of magnitude. Localised melting can become a runaway process. MkI design allowed for 1mm tolerance of installation. A detailed survey showed that ≤0.5mm was achieved rail-to-rail.

The tiles were produced by a Brush-Wellman standard manufacturing process out of S65c powder. A near net shape could be achieved on most faces; the faces seating on the support rail and the plasma facing area was machined to better than 0.05mm tolerance.

3. ELM INTERACTION WITH MKI TILES

The divertor configuration of JET and other large tokamaks admits discharges for which short duration bursts of energy (and particles), ELMs, interact strongly with tile material. One set of discharges, a search for the limits to an ELM-free discharge, produced a large ELM whereby approximately 1MJ of stored energy was lost in 100μsec. The footprint of the ELM involved an interaction area of ~0.15m^2. Melting patterns on tile pairs adjacent to and outboard of the centre line of the base cf. figure 1 show that energy was deposited at a glancing angle of incidence, typically ~0.5°. Assuming 50% radiation this implies a peak flux density of approximately 35 × 10^{3}MW/m^2. Beryllium melting is expected after ~20μsec. Taking into account melting and evaporation, this implies a layer of no more than 0.5mm resolidified material.

The mechanical properties of beryllium are subject to strain-rate effects. Calculations show that strain-rates of ~5 × 10^2/second at the surface are achieved. However, these same calculations show that large strain-rate effects on such a short time scale are confined to near-surface regions which are melted and later solidified. The flux densities incident in an ELM may locally, e.g. on exposed shoulders of a castellation, be high enough to produce vaporisation with little trace of the melted material. Such regions in the MkI design are covered by resolidification of neighbouring material as the affected areas are extremely small.

In the design of an actively - cooled beryllium component the principal problems are of lifetime assessment (loss of material through evaporation or mechanical displacement) due to ELMs. There is a serious problem of residual stresses in the bonded region due to resolidfication of molten material. As the rate of resolidification in a vacuum environment is not determined by incident flux density during a ELM event the JET experience of no visible mechanical damage to the roots of a castellation due to ELM events is encouraging.

Figure 4. Section of resolidified zone due to single giant ELM crash

4. METALLURGICAL INVESTIGATION

The material melted and resolidified in the ITER-dedicated experiment has been sectionned. Near surface regions are seen to be cracked with long columnar crystals as expected. The roots of castellations were also examined and a crack was seen to have developed at the base, cf. figure 3. Only 1 out of 3 positions examined was shown to have cracked. A more detailed investigation is to be done shortly of this process.

The material melted and resolidified as a result of the single giant ELM crash has also been examined. One section showing long curving fatigue cracks is shown in figure 4. These cracks appear to propagate into the virgin material, i.e. to extend below the resolidified zone. More detailed investigations are in hand.

5. NUMERICAL ANALYSES

Thermo-mechanical assessment of the MkI tiles was carried out largely based on a 2-d picture for thermal calculations with a full 3-d model for the footprint onto a tile. During design a 2-d plane - stress assessment was made. Assessment of actual equilibria required 3-d thermal and mechanical analyses. Plastic zones, ~0.5% equivalent strain develop over most of the irradiated face, also along edges. Only 3-d analyses obtain this last result. Fatigue cracks parallel to the irradiated face have been seen on some MkI melted tiles.

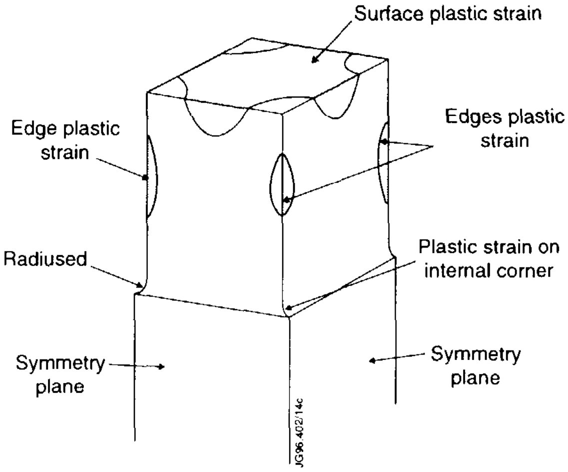

Figure 5. Plastic zones of typical castellation prior to melting

6. CONCLUSIONS

Metallographic studies of the resolidified beryllium region shows characteristics previously observed, microcracks along columnar boundaries, local cracking of the virgin material. Some evidence is seen for lateral cracking at the edges of strongly heated/resolidified castellations. Evidence is seen for crack initiation at the base of a castellation subjected to deliberate melting on several shots.

Attempts to analyse for the consequences of melting on crucial areas of the tile, i.e. roots of castellations show that a full 3d analysis appears to be mandatory though a failure of either plane-stress or plane-strain analyses to take proper account of the diffusion of thermal stress into a typical castellation. As yet there is no evidence to support numerical predictions of large plasticity zones at roots of castellations.

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