**The challenges in predicting the fatigue life of dissimilar brazed joints and initial finite element results for a tungsten to EUROFER97 steel brazed joint**

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This paper summarises the challenges in accurately predicting stress states in dissimilar brazed joints and presents initial results from a finite element analysis of a tungsten to EUROFER97 brazed joint. The residual stresses due to joint manufacture are presented and differences in stress distribution due to thermal and mechanical loading highlighted. The results from this analysis correlate well to experimental results from previous research however further validation is required. The challenges in developing fatigue assessment procedures for dissimilar brazed joints are also discussed. These fatigue assessment procedures are introduced and a validation strategy for such procedures is proposed.

Keywords: finite element analysis, braze, joint, tungsten, EUROFER97, fatigue,

**1. Introduction**

The development of a He-cooled divertor for a demonstration reactor (DEMO) is dependent on the reliable joining of refractory metals such as tungsten and reduced activation ferritic-martensitic steels such as EUROFER97 [1]. One of the joining technologies currently being developed is high temperature brazing [2,3]. Due to differences in material properties between tungsten and EUROFER97, high stresses can occur as a result of the joining process in addition to the thermal and mechanical loading. Under cyclic loading the presence of these high stresses can result in fatigue and other forms of failure [4].

Due to the presence of analytical singularities, complex stress states in the region of the joint and the lack of material property data for brazed layers, no robust technique exists at present to predict the stress states in such joints and consequently allow joint fatigue life estimations. Therefore practical procedures are being developed to assess both the design and the fatigue performance of brazed joints under different types of loading. The procedures aim to be generic and account for residual stresses due to the manufacturing, plasticity, brazing technique and geometry of the joint.

The challenges that must be addressed when modelling dissimilar brazed joints are discussed in this paper along with results from an initial attempt to model a tungsten to EUROFER97 brazed joint. Future work on developing methods to assess the fatigue of brazed joints, the validation strategy for these procedures and proposed design sensitivity studies are also discussed.

**2. Previous work on the modelling and fatigue of dissimilar brazed joints**

Finite element modelling of dissimilar brazed joints has been the subject of previous research. Chehtov [3] used finite element analysis to predict the stress distribution in a tungsten to EUROFER97 brazed joint. This research modelled the braze layer as a homogenous material with uniform material properties and predicted the stress distribution due to cooling from an assumed stress free brazing temperature. Reiser [5], developed techniques to model a conical tungsten to EUROFER97 brazed joint, however it does not account for the presence of the brazed layer. You [6,7], used finite element analysis to predict the residual stresses in a dissimilar brazed joint and subsequent stresses under repeated thermal loading.

Additionally, Jiang [8], Gong [9], Galli [10] and Vaidya [11] have also developed finite element techniques to predict the residual stress fields in dissimilar brazed joints with a limited number of validation tests performed on brazed specimens. Despite initial research into developing finite element models to predict the stress state in dissimilar brazed joints, at present there are no techniques which take into account all the factors described in the following section.

Compared to the fatigue of welded joints, relatively little work has been published on the fatigue of dissimilar brazed joints. Copper to silver and copper to tungsten brazed joints have been subjected to rotating bending and axial displacement control mechanical fatigue testing [12-14]. Copper to tungsten brazed joints have also been tested under thermal cyclic loading [15]. High heat flux testing facilities have also been extensively used to assess the integrity of dissimilar brazed joints [16].

Research into the development of methods for predicting the fatigue of brazed joints under mechanical and thermal loading is scarce. A fracture mechanics based approach has been developed by Seki [14] to estimate the fatigue crack propagation life of small defects in a brazed layer, however, this does not consider the scenario where cracks initiate in the parent materials where it is known to occur [2,15]. You [6] proposed using the approach detailed in ASME III [17] to predict life of either of the parent materials and Carter [18] detailed a method for predicting fatigue lives of brazed joints in heat exchangers. Both methods however do not account for the individual geometry of the joint and the complex stress fields through which a fatigue crack would propagate.

**3. The challenges in modelling brazed joints and developing fatigue assessment procedures**

**3.1 Residual stresses due to joint manufacture**

Due to differences in material properties and high brazing temperatures, high residual stresses can be present in dissimilar brazed joints due to joint manufacture. The presence of these residual stresses is widely known and has been discussed in detail in previous research [2,11]. These residual stresses cannot be eliminated by stress relief due to the dissimilar materials used. From an analytical perspective, these locked in stresses due to manufacturing must be accounted for when trying to predict the stress state in the brazed joint.

**3.2 Microscale considerations**

Due to the relatively small thicknesses of brazed layers (c. 100µm), there are certain microscopic features that must be taken into consideration when modelling a brazed layer. Firstly, for a copper to 316LN joint brazed using a nickel based brazed filler, it has been found [19] that there is a diffusion region approximately 10µm thick where traces of the brazed layer can be found in the parent material. Nano-indentation testing has shown that the hardness and Young’s modulus properties in this region are within 10% of those of the parent material. Hence, it is argued that this region can effectively be ignored in any finite element approximation of the joint in this case.

In addition, in a copper to 316LN steel joint, inspection of the brazed layer has shown that the microstructure consists of two distinct nickel based phases. Nano-indentation testing across the brazed layer [19] has shown large variations in hardness and Young’s modulus. Clearly, big differences in material properties must be considered carefully, and work is ongoing to address these issues. Work is also ongoing to establish the effect of different brazed layers and thicknesses on the stress distributions in brazed joints. If the brazed layer has to be accurately modelled and accounted for in finite element models, temperature dependent material property for the braze data will also have to be generated.

**3.3 The presence of analytical singularities**

Due to the nature of brazed joints, analytical singularities exist in finite element models at the free surface edge of the joint interface, their strength being a function of the degree of dissimilarity between the material properties. The stresses obtained at this interface are non-converged and a function of mesh refinement. The existence of these singularities is widely recognized and work has been done to understand and quantify the stress states in such regions [20]. The approach used for this work to quantify the stress at the singular interface is the hot-spot stress approach used in the fatigue assessment of welded joints [21]. Part of developing the proposed fatigue assessment methods will involve determining the rules (mesh sizes, sampling distances and extrapolation type) that are to be used for hot-spot stress extrapolation.

**3.4 Failure of brazed joints in a plasma facing component**

Before a life assessment is performed, the fatigue failure criteria must be established for a tile in a plasma facing component. Tiles tend to fail due to overheating [22,23] as fatigue cracks reduce the ability of the tile to conduct heat from the plasma facing surface to a visible cooling channel. From a fatigue perspective there are three scenarios which could result in failure of the tile. Firstly, a tile could be deemed to have failed after a crack has initiated. However using this as a failure criterion would give an overly conservative estimation of component life as the initiation of a crack is unlikely to cause severe overheating.

Secondly, a tile could be deemed to fail if cracks initiate and propagate such that the tile detaches. High heat flux testing has shown [22,23] that overheating can occur due to cracking without a tile detaching. Therefore, assuming tile detachment as a failure criterion is not suitable.

The third scenario occurs when a crack initiates and reaches an unacceptable propagation length which results in substantial overheating. High heat flux testing has shown this to be the case [22,23]. The acceptable length will be dependent on tile geometry hence a practical life assessment procedure must be able to predict number of cycles for a crack to reach a certain length.

**3.5 Varying failure locations**

Cyclic testing has shown that dissimilar brazed joints fail at different locations under different types of loading. Kalin [2] showed that cracks initiate in the tungsten section of a tungsten to EUROFER97 steel brazed joint when subjected to cyclic thermal loading at approximately 100µm away from the braze layer. Similarly, Brossa [15] showed that cracks initiate and propagate in the tungsten section of a tungsten to copper brazed joint a small distance away from the brazed interface under cyclic thermal loading.

Under rotating bending mechanical loading, Solomon [13] has shown that copper to copper brazed joints mainly fail through the brazed layer. This has been attributed to defects in the braze. If however the braze layer was of good quality, the joints were found to fail a small distance away from the braze layer. This has been attributed to the braze layer having superior mechanical properties to the parent copper material. Additionally Seki [14] has shown that cracks propagate in a tungsten to copper brazed joint in different directions during rotating bending tests at room temperature and at 200°C. Any procedures developed to predict the life of such joints must be robust and capable of accounting for all failure case characteristics described above.

**4. Initial finite element results**

**4.1 Model Formulation**

Techniques are being developed to predict the complicated multi-axial stress state present in tungsten to EUROFER97 brazed joint. These techniques aim to address the issues outlined in the previous section and account for the presence of the brazed layer, residual stresses, temperature dependant elastic / plastic material properties [3,24,25] of both the brazed layer and the parent materials. A simple butt joint of cylindrical tungsten and EUROFER97 steel specimens (diameter 4= mm, height = 5mm) with a nickel based brazed filler (BNi-2 (Nibal-7Cr-4.5Si-3.1B-3Fe-0.06C), height = 0.1mm) has been modelled using ANSYS. Residual stresses due to manufacture have been determined by cooling the joint from an assumed stress free state at 1000°C to room temperature. The levels of residual stress will also be influenced by primary creep however this has been neglected in this work. Two subsequent loading scenarios are then considered, the application of bulk temperature heating to 600°C and the application of a 140MPa uniaxial mechanical load. In practice the operational temperature of EUROFER97 as conventional RAFM steel is limited to 550°C.

**4.2 Convergence studies**

Convergence studies have been performed with mesh refinements up to 6.25µm (16 elements across the brazed layer). Results show that to obtain a detailed understanding of the results across the brazed layer, such high mesh refinements are required. Even with highly refined meshes such as this, results in the proximity of the join remain non-converged due to the presence of the aforementioned singularity. With further increases in mesh refinement, the decay length of the singularity will decrease however these non-converged results will remain.

Hence, to quantify the stress range at the joint interface, hot-spot stress techniques are currently being developed to extrapolate the converged stresses in the region of the joint to a hot-spot stress at the interface. Analysis shows that the peak stresses are in the axial direction and are at a maximum at the free edge of the joint. Hoop stress distributions exhibit a similar singular behaviour however are an order of magnitude lower than the axial stresses at the free edge. That is not to say that they will be unimportant in any assessment procedure.

**4.3 Residual axial stress distributions**

Results show that residual stresses due to cooling results in tensile stresses in the tungsten and compressive stresses in the steel region of the joint. This is in agreement with the analytical solution [2] and research with similar materials [11] however the magnitude of these stresses needs to be validated. The magnitude of these stresses causes plasticity in the EURORER97 steel. The free edge residual stress distribution across the brazed layer and in the parent materials adjacent to the brazed layer is shown in figure 1. The magnitude of these stresses highlights the importance of including them in any finite element analysis of brazed joints.

**4.4 Subsequent thermal and mechanical axial stress distributions**

The free edge axial stress distributions across the brazed layer due to thermal and mechanical loading are also shown in figure 1. The results show that stress distributions are completely different under the different loading scenarios. Given these stress distributions, from a fatigue perspective, it is likely that under either thermal or mechanical loading, cracks will initiate in the tungsten due to the large stress range about a tensile mean stress. This finding is in agreement with previous research [2].

Fig 1 - Free edge axial stress distributions in a tungsten to EUROFER97 brazed joint

**4.5 Through thickness stress distribution**

Given this likely fatigue crack initiation site, the radial axial stress distribution will govern how the crack propagates. Shown in figure 2 is the axial stress distribution from the position of maximum converged tensile stress in the tungsten for 0.5mm radially inwards. Cracks due to repeated thermal or mechanical loading will propagate at different rates to due to the different through thickness stress distribution.

Fig 2 - radial axial stress distribution

**5. Current and future work**

**5.1 Development of fatigue assessment procedure**

Procedures are being developed to assess the fatigue performance of such joints under both thermal and mechanical loading. These methods are based on using a classical S-N type approach where the fatigue performance of the joint is related to the fatigue performance of specimens made from each parent material. A fracture mechanics based assessment procedure using XFEM capability in ABAQUS is also being developed. Fracture mechanics can also be used to assess any flaws, voids or inclusions created during the brazing process. These procedures aim to be generic and account for residual stresses due to joint manufacturing, plasticity, brazing technique (filler material and brazing temperature) and the geometry of the joint.

**5.2 Experimental validation**

To validate the finite element procedures being developed it is proposed to use x-ray diffractometry to measure residual stresses due to manufacturing. In addition, to validate the fatigue assessment procedures, cyclic thermal, rotating bending and uniaxial mechanical loading fatigue tests will be performed on brazed joints to confirm crack initiation sites and also study crack propagation through the specimen. Any fatigue assessment procedure must be able to accurately predict the fatigue crack initiation site and number of cycles for a crack to reach a certain length.

**5.3 Brazed joint design sensitivity studies**

When fully validated finite element procedures have been developed to predict the multi-axial stress distribution in brazed joints, it is proposed to carry out a series of design sensitivity studies to evaluate different brazed joint designs. Parameters such as parent / brazed layer material properties, joint dimensions, brazing temperature, the use of interlayers and functionally graded transitions materials will all be investigated.

**6. Conclusions**

The challenges faced in modelling and developing procedures to assess the fatigue performance of brazed joints have been discussed. If accurate stress states and hence fatigue lifetimes are to be predicted, these challenges must be overcome. Initial attempts to predict the stress state at the interface of a tungsten to EUROFER97 brazed joint has been presented. The results correlate well to experimental results from previous research, however further validation is required. In addition, work is currently underway to develop fatigue assessment procedures for brazed joints. Procedures based on using traditional S-N type approaches and fracture mechanics have been proposed. The final procedure will be validated against cyclic thermal and rotating bending and axial fatigue tests and will be informed by initial results from these tests.

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