

NORMATIVE ISSUES IN THERMAL FATIGUE

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ABSTRACT

The design of components subjected to thermal fatigue is one of the most challenging tasks for the experimental thermonuclear fusion reactor project. In this paper the applicability of the present existing nuclear standard codes (ASME and RCC-MR) is discussed. Problems of numerical modelling and the design of technological components are tackled.

1 INTRODUCTION

Thermal fatigue seems to be one of the most lifetime limiting causes of the experimental fusion reactor first wall (FW). This is the component which covers about eighty percent of the surface facing the thermonuclear plasma and is considered a permanent component of the reactor. The reference material is AISI 316L stainless steel. In the framework of the European Fusion Technology programme a theoretical and experimental activity is in progress in the Institute for Advanced Materials of the Joint Research Centre oriented towards manufacturing problems and towards checking the lifetime under thermal fatigue. The approach to this problem is multidisciplinary, with a balance between theoretical analysis and experimentation. Both simple components and FW prototypes are used in the thermal fatigue experiments. The former are manufactured by machining, have a simplified geometry and smaller dimensions and do not contain welded or brazed joints; they are tested to validate the numerical results and the fatigue life evaluation procedures. Part of this context is the benchmark initiative carried out by the International Atomic Energy Agency (I.A.E.A.) of Vienna, in which European, Russian and Japanese laboratories have taken part. This initiative is aimed at comparing the results of elastoplastic calculations performed with finite element codes by each participant and the duration of life under fatigue is then evaluated following the criteria adopted in the various countries. This phase was followed by a comparison of the lifetime predictions with the experimental results obtained in components of the same geometry and in the same thermal load conditions as those assumed as a basis for the calculation. Prototypical components are made using the manufacturing techniques used for the real corresponding FW concept; beyond the validation of the numerical calculations, they respond to the need to check the influence of alternative manufacturing methods on thermal fatigue lifetime.

The aim of the present paper is to discuss the normative critical points of the standards which have emerged and which deserve attention when designing

components subjected to thermal fatigue.

2 THERMAL FATIGUE DESIGN

A component subjected to cycling thermal stress must be designed to withstand the target number of cycles without being damaged in an unacceptable way. The expected number of fatigue cycles must be lower than the maximum allowed fatigue cycles determined according to the adopted standard. In this process four main points must be considered.

At first it is worth pointing out that the failure state is not a universal concept in thermal fatigue. In fact, while the definition when applied on a simple component subjected to mechanical cycles is straightforward, it is more subjective to give the correct definition of what 'failure' is if we have only thermal stress. Generally speaking, in the case of primary loads the deeper the crack the faster it propagates; on the other hand, a crack does not necessarily propagate to component failure under a purely thermal stress driving force in a FW geometry. In fact, in the thickness between the surface heated by the thermonuclear plasma and the cooling channels, there is a stress-free plane in which a crack is likely to stop. The French RCC-MR code defines damage as *the appearance of small macroscopic cracks which do not compromise the strength of the structure with regard to the other types of damage to be considered*. This definition can be considered to be valid also in thermal fatigue but it should be pointed out that it may lead to subjective evaluations and to some difficulties if several experimental data are to be compared.

The second point to be discussed includes the numerical analysis of thermal fatigue and the sensitivity of different modelling approximations in the evaluation of the stress.

The third point is how to determine the maximum allowed number of cycles from the history of stress and strain. In fact, even if standards specify procedures for this purpose, different interpretations may lead to different results as explained later.

The last but not least problem is if and how to take the different manufacturing techniques into account in the thermal fatigue design.

All of these three points will be discussed below.

3 NUMERICAL ANALYSIS OF THERMAL FATIGUE

The reference thermal fatigue experiment of the above-mentioned benchmark exercise consisted in a specimen (300x78x44 mm, see fig. 1) in which five cooling channels were obtained by drilling. Their axis were parallel to the main dimension and located 14 mm below the heated surface, the inner diameter was 8 mm. The coolant was deionized water. Opposite the heated surface, two water collectors were TIG welded. Further details on the experiment can be found in ref. 1. The heat flux reached a value of 520 kW/m^2 during the heating phase of the thermal cycle which had a total duration of about 3 minutes.

All the participants performed the numerical analysis starting from exactly the same material data and test conditions using the finite element technique. A complete report of all the calculations performed can be found in ref. 2.

Let F be the point located at the centre of the heated surface. As far as the thermal transient analysis is concerned, the maximum computed temperature in F ranges from 384 to 390 °C with a scatter below 2%. As regards the elastic analysis, the Von Mises equivalent stress ranges from 662 to 963 MPa

with a difference higher than 30%. Even more unexpected results were obtained from the elastic-plastic analysis: the spread of the Von Mises equivalent stress was more than a factor of 2, ranging from 192 up to 394 MPa. The mechanical strain range, which is adopted by the RCC-MR to determine the allowed fatigue life, had a minimum computed value of 0.424% whereas the maximum figure was 0.605% with a difference of about 40% .

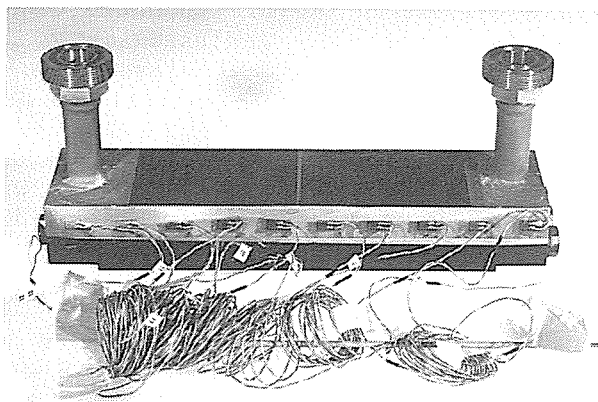


Fig. 1 - The IAEA benchmark component

3.1 Discussion of the results

Thermal stress evaluation is quite different from mechanical stress evaluation. In the latter case, stresses are directly computed in order to equilibrate applied loads which generally constitute a well defined set of input data. On the other hand thermal stresses cannot be directly computed as they are *self-induced* stresses which arise in order to guarantee the continuity of the structure; they can be computed by a calculation which has another calculation as an input, the thermal transient analysis. This has an immediate consequence: having fixed all the other conditions, thermal stresses are more influenced by the numerical procedure adopted and are therefore characterized by more uncertainty.

Standard codes give no recommendations about the way in which the mechanical analysis (both elastic and elastoplastic) should be performed even if only the so-called *generalised plane strain* (GPS) modelling approximation is meaningful in a 2D computation. In fact the *plane stress* model gives unduly optimistic results whereas the *plain strain* model is unrealistically conservative. On the other hand, it is worth noting that not all the finite element method computer programs can manage the GPS method and therefore one can be forced to adopt an unsuitable method, as sometimes happens. Even more insidious is the case in which GPS is implemented but with the 'bending constrained' characteristic. Without entering in the modelling details it is enough to say that in this case also the results are very pessimistic in spite of the use of GPS.

As regards the elasto-plastic analysis, it should be emphasized that, according to how the material hardening is modelled, very different results can be obtained. The RCC-MR code suggests (but does not impose) a method based on the kinematic hardening rule and a stress-strain bilinear relation obtained by the so-called *reduced cyclic curve*. But other analysis methods are available and well-established. Of these one need just mention the ORNL-TM-3602 recommendations. Unfortunately, the adoption of one or the other of these methods can lead to rather different results.

4 EVALUATION OF THE DESIGN-ALLOWABLE CYCLES

All the laboratories involved in the benchmark exercise determined the design-allowable cycle according to the procedures stated by the nuclear codes. Point F proved to be the most stressed location. The RCC-MR application based on the elastic analysis led to a number of cycles ranging from 400 to 6500 with a difference of more than one order of magnitude. A factor of 5 is the scatter in the case of elastoplastic analysis. The lower spread is due to the fact that the RCC-MR elastic procedure can provide different results according to the possible application of notes 2 and 4 of section RB 3261.1.2.3, pp. 54-56 (RCC-MR June 1985 Ed.).

The thermal fatigue test was stopped after about 52,000 cycles. Fig. 2 shows one of the deepest cracks observed on the F location. The surface was chemically etched; branching of the crack is visible. It is 0.43 mm deep and proved not to decrease the performances and the safety of the component appreciably. An analogous experiment, stopped after 33,000 cycles, showed cracks having about the same depth but with a lower the density of surface crack population. Therefore it seems that cracks do not propagate but only increase in number as the number of fatigue cycles increases.

In any case it is worth mentioning that the maximum allowed number of cycles found by the laboratories is far below the experimental result.

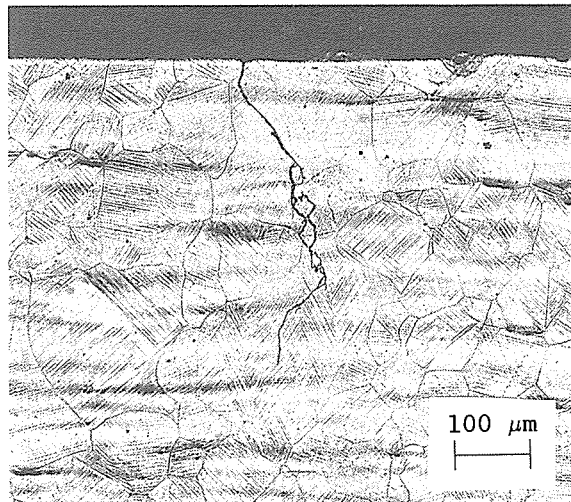


Fig. 2 - Thermal fatigue crack

5 INFLUENCE OF THE MANUFACTURING TECHNOLOGY

Two FW prototypes manufactured by Ansaldo Ricerche and Framatome were tested. The technology developed by the former envisages a first vacuum brazing of two half-plates, milled to obtain the cooling semichannels; the second phase consists in the insertion of tubes without welding into the channels and in their junction to the plate by means of a second vacuum brazing, at a lower temperature. In the Framatome component (fig. 3) the junction of the half-plates is made by means of transparency electron beam welding; one obtains plates with four cooling channels which are then welded together, again with an electron beam. The final phase of insertion and junction of the internal tubes is similar to the Ansaldo process.

After less than 5,000 thermal fatigue cycles a loss of coolant occurred in the Ansaldo component through a crack which started from the brazing of the two half-plates. The Framatome component showed a long and deep crack in the

electron beam welding which joined the two plates with four cooling channels each. It is worth noting that, according to the numerical analysis, in both the components, the Von Mises equivalent stress in the location where the crack nucleated, was one fourth the maximum value computed on the heated surface. In this surface no visible flaws were detected.

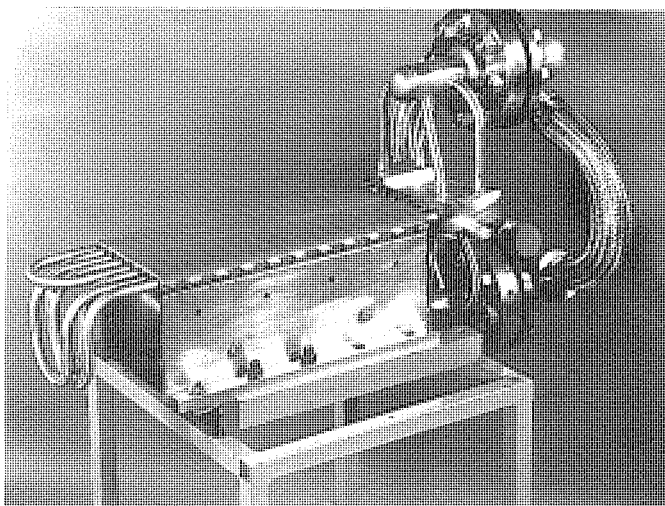


Fig. 3 - The FW prototype manufactured by Framatome

5.1 Discussion of the results

The results obtained with the prototype components deserve attention. In fact fatal damage was observed in those locations where standards guaranteed a much longer lifetime. The deleterious effects of the brazing and electron beam welding on the thermal fatigue lifetime are therefore evident.

RCC-MR deals extensively with the problem of welded joints but it does not tackle brazing whereas electron beam welding is treated in section RS-3560. ASME deals with welded joints in section IX part QB. In any case only qualification procedures are provided and no specific fatigue design rules are given concerning brazing or electron beam welding. The lack of a specific design procedure as well as the worrying experimental results leads us to investigate whether a solution to the problem can be found within the standards.

An answer can be given by both ASME (sect. III, div. I, subsect. NB-3213.3) and RCC-MR (sect. I, subsect. RB-3221.2), where the *local structural discontinuity* is defined. In fact it is a *geometric or material discontinuity which only affects the distribution of stresses or strains in a small part of the wall thickness. The stress distribution resulting from this type of discontinuity causes only very localized deformations and has no significant effect on the overall deformation of the wall.* Both brazing and electron beam welding fit this definition as their thickness never exceeds a few hundred of microns and their stress intensity effect is very localized and is due to the different thermal and mechanical properties of the joint with respect to the base material.

RCC-MR does not give specific guidelines as regards local structural discontinuity. A priori the only possibility seems to be the *experimental analysis* described in subsect. RB-3213. It consists in *subjecting models representing the component (...) to loadings in order to determine the deformation and stresses or margins with regard to the damage under study.* No

details are provided about the way in which the experimental results should be taken into account in the design of the real component, nor on which safety factor should be used.

ASME describes the procedure to follow in the case of local structural discontinuities in sect. III, div. I, subsect. NB-3222.4(e2). Some possibilities are proposed but the only one which may be realistically applied is the *experimentally determined fatigue strength reduction factor (...) determined in accordance with the procedure of II-1600* (sect. III, div. I, app. II). This procedure envisages experimental tests on two similar components: the former containing the discontinuity and the latter not. This is rather impractical for FW prototypes because of their high cost and the relatively long time needed to perform a thermal fatigue test.

We are therefore in a situation where *theoretical stress is inadequate or (...) design rules are unavailable* (ASME sect. III, div. I, app. II-1111). When such a situation occurs in the case of cyclic loading, the procedure to follow is described in detail in app. II-1510. Specific requirements for cyclic testing of components are provided. It also shows how to take into account the effect of size, surface finish, test temperature, the statistical variation in test result and the differences in design fatigue curves at various temperatures.

6 SUMMARY AND CONCLUSIONS

A critical analysis of the numerical and experimental results has identified three main critical issues in the design of a component subjected to cycles of purely secondary stress.

(1) The way in which thermal stress is numerically evaluated may strongly influence the final result, therefore more precise guidelines are required in order to reduce the extent of arbitrary choice by the analyst. (2) The standard procedures to assess the design-allowed number of fatigue cycles need some more consideration if applied to purely secondary stress. (3) Experimental evidence on prototypical mock-ups has revealed that thermal fatigue lifetime is greatly influenced by the manufacturing process. Therefore regions where the standard codes assure a high design-allowable number of cycles can prove to have a much shorter safe lifetime, and vice versa. On the other hand, the base material shows a strong resistance against thermal cycling loads.

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REFERENCES

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