FATIGUE LIFE PREDICTION OF A STAINLESS STEEL PLATE-FIN STRUCTURE USING EQUIVALENT-HOMOGENEOUS-SOLID METHOD

Wenchun Jiang, J M Gong, S T Tu
School of Mechanical and Power Engineering, Nanjing University of Technology, Nanjing 210009, PR China
Jiangwenchun@126.com

Abstract
Stainless steel plate-fin heat exchangers are key components in nuclear power stations and hydrogen production systems using High Temperature Gas-cooled Reactors (HTGR). This paper establishes a life prediction method of fatigue based on equivalent-homogeneous-solid method for a 304 stainless steel plate-fin structure. A finite element analysis of fatigue life has been developed and verified by fatigue experiments. By using this method, both the local stress concentration and the fatigue life for plate-fin structure can be predicted. The results of FEM and experiments show that the fatigue cracks initiate at the fillet and then propagate to the base metal of fin. The fatigue fracture in the filler metal shows brittle character, while typical dimple and striation are shown in the base metal.

Key words: Stainless steel plate-fin structure; Fatigue life; Finite element analysis; Equivalent homogeneous solid method

1. Introduction
Stainless steel plate-fin heat exchangers (PFHE) are key components in nuclear power stations and hydrogen production systems using High Temperature Gas-cooled Reactors (HTGR) [1]. The advantages of stainless steel PFHE are high efficiency in heat transfer, compact structure, high-pressure resistance, excellent high-temperature mechanical properties such as high creep strength compared to conventional aluminum PFHE [2]. Therefore, stainless steel PFHE is mainly used at high temperatures and pressures, such as nuclear heat utilizations [3], recuperative gas turbines and combined cycles, recuperative micro-turbine systems [4], etc.

Fatigue is the most failure mode for stainless steel plate-fin structures because they operate under cyclic high pressures and elevated temperatures. However, the previous researches are focused on Aluminum PFHE, and little attention has been paid to stainless steel PFHE. Carter [5] found that the failure mechanism was fatigue and the cracks were generated in the fillet for an Aluminium PFHE. Yao [6] established a life prediction method of fatigue for AlMn1.0Mg0.5 filler alloy using the modified universal slope method. Takehiro [7] performed fatigue tests to a local position consisting of a parting sheet and two side bars for an Aluminium plate-fin structure, through which the fatigue life prediction method was estimated. The above literatures are just focused on the local position of plate-fin structure, and the life prediction method of fatigue for the whole plate-fin structure has not been established yet for its structure complexity. In recent
years, finite element method (FEM) has been widely used to predict the fatigue life for the complex structures [8–11]. This paper tries to predict the fatigue life of the whole plate-fin structure by FEM.

The homogeneous method was firstly developed for composites with periodic and quasi-periodic internal structures [12–14]. This method has the capability of evaluating both macroscopic constituent behavior and microscopic stress distribution. In the field of structure design of heat exchangers, the homogeneous approach was also introduced to predict the equivalent mechanical parameters of tube-sheet [15] and perforated-plate structures in HTGR [16–18]. Due to the periodic characteristics of the plate-fin structure, this paper tries to establish a life prediction method of fatigue using the homogeneous approach combined with finite element method.

2. Material and experimental procedure

2.1 Vacuum brazing of plate-fin structure

In this paper, both plate and fin materials are 304 stainless steel. The filler metal is BNi-2. In this paper, the tensile and fatigue test specimens will be prepared. However, one problem is that there is no clamper for this thin and complex structure. The solution is as follows: Two solid pieces (304 stainless steel), which provide the clamper position for the tests, are brazed at the top and bottom. Before stacking, fins, plates and solid pieces are degreased, acid etched, detergent washed, rinsed and oven dried. After stacked, the plate-fin assembly is fixed and brazed in vacuum furnace.

This plate-fin structure is fabricated by vacuum brazing. The thickness of fin and plate is 0.2 and 0.4mm, respectively. The initial filler metal thickness is 105µm. The brazing heating cycle consists of seven steps. At the beginning, the furnace is vacuum pumped to 0.001Pa (step 1). The stacked plate-fin structure is heated to 850°C within 50min (step 2). The temperature is held for about 30 minutes to reduce the temperature gradient of the whole assemblies (step 3). Then heating is resumed to the brazing temperature of 1050°C within 30 minutes (step 4), which will lead to the best capillary flowage of nickel-base filler metal. According to the thickness of base metal and the complexity of the structure, brazing time is controlled in 25min (step 5), which enables the carbide of the austenitic stainless steel to achieve preferable solid-solution treatment. The cooling composes of two steps. The first is self-cooling in vacuum from 1050 to 620°C (step 6), which needs about 40mins. The purpose of this step is to release the residual stresses at elevated temperature, avoid thermal cracks, and increase the strength. When the temperature is lowered to 620°C, the quick cooling is performed by filling the furnace with dry nitrogen and starting-up the wind cooling system at the same time (step 7), which lasts about 50 minutes. Then the brazed plate-fin structure is moved out the furnace to cool in air when the body temperature is about 40°C.

2.2 Tensile test of plate-fin structure

The brazed plate-fin structure is machined and the tensile test specimen is made through lining cutting. The test specimen has rectangle cross-section of 120mmx25mm. It consists of three layers of fins, two plates, and two solid pieces on the top and bottom. The tensile test is performed at Instron 5869. During the test, the specimen is strained to failure at a constant loading velocity of 0.5mm/min. The macroscopic stress is determined by dividing the tensile load to the cross-sectional area of 25mmx3mm. The macroscopic strain is determined by dividing the displacement to the height of three layers of plate-fin part.

2.3 Fatigue test
The brazed plate-fin structure is machined into the fatigue test specimen through lining cutting. The test specimen shape is similar to that of the tensile specimen, but the difference is that it has rectangle cross-section of 220mm x 22mm.

Subsequent to the specimen preparation, the fatigue tests of 304 stainless steel plate-fin structure specimens are done on a servo-hydraulic MTS 810 testing machine. The test temperature is 600°C. A serious of stress-controlled mechanical tests is performed with a sine waveform loading. According to the tensile strength and the actual operating pressure of plate-fin structure, four different stress amplitude of 5.4, 8.1, 9.4, 10.8 MPa are applied. The R-ratio is kept to \( \sigma_{\text{min}}/\sigma_{\text{max}}=0.1 \). The test frequency is 2 Hz. Each experiment is repeated multiple times to reduce the likelihood of bad data.

3. Finite element analysis of fatigue life

3.1 Fatigue parameters approximation by Seeger’s method

It can be found that the fatigue tests in Section 2 are complex and cost. Moreover, the FEA of the whole plate-fin structure will result in extraordinarily large numbers of nodes and elements. Hence, it is important to develop simplified method for fatigue life prediction for this complex plate-fin structure. In this paper, the overall plate-fin structure is modeled to an equivalent homogeneous solid plate instead of modeling the local structure of plate-fin. Using this method, the fatigue life is analyzed to the equivalent plate by ABAQUS-FESAFE. FESAFE software is a powerful, comprehensive, and easy-to-easy suite of fatigue life analysis. It has a direct interface to FE software ABAQUS and the results of fatigue life can be presented as contour plots in ABAQUS. FESAFE is supplied with a compressive database containing fatigue properties for commonly used materials. However, for the present plate-fin structure, its material properties are not available. But the material properties can be approximated by using the Approximate Material Function. This function uses Seeger’s method to generate approximate fatigue parameters based on tensile strength \( \sigma_u \) and Elastic modulus \( E \).

The tensile strength can be obtained by tensile test in Section 2.3, and the Elastic modulus can be obtained by FEA in Section 3.1.

3.2 Prediction of equivalent elastic modulus

ABAQUS Version 6.5-1 was used in this analysis. Four-node iso-parametric elements were employed. The number of elements was 18 408, and the number of nodes was 20 096. Under the plane stress condition, tensile displacement \( \delta \) was loaded up to 0.04 mm (equivalent to the macroscopic strain of \( \varepsilon^* = 0.2\% \)), and the stress–strain curve was obtained. The Elastic Modulus can be calculated form the stress-strain curve.

3.3 Finite element analysis of fatigue life

In this section, the whole plate-fin structure is modeled to an equivalent homogeneous solid plate, as shown in Fig.5. The research object is changed to a plate instead of the complex plate-fin structure. Firstly, the stress is analyzed by a linear elastic FEM in ABAQUS. Then the nodal stress is imported to FESAFE and the fatigue load is defined. The required material properties are obtained by Approximate Material Function described in section 3.1. Then the fatigue life analysis is performed and the results are plotted in ABAQUS.

4. Results and discussion

It can be found that the tensile strength is around 33.3 MPa. It is calculated that the Elastic modulus is 8.51 GPa. Here the stress \( \sigma = (\text{load})/(\text{cross-sectional area}) \), strain \( \varepsilon = (\text{displacement} \delta \text{/gage length} L (=19.73 \text{ mm})) \). It is shown that the Young’s modulus and tensile strength of the whole plate-fin structure is lower than that of base material.
In total, the results show a good agreement between fatigue experiment and FEA. A small difference exists because that the effect of brazing flaws was not considered in finite element analysis. Using this method, both the local stress concentration and the fatigue life of the whole plate-fin structure can be predicted. The fatigue life prediction for plate-fin structure is thus established by the equivalent-homogeneous-solid method.

5. Conclusions

This paper establishes a life prediction method of fatigue based on the equivalent-homogeneous-solid method for 304 stainless steel plate-fin structures. A finite element analysis of fatigue life has been developed and verified by experiments. By using this method, both the local stress concentration and the fatigue life of the plate-fin structure can be predicted. The results of FEM prediction and experiments show that the fatigue cracks initiate at the fillet and then propagate to the base metal fin. The fatigue fracture in the filler metal shows brittle character, while typical dimple and striation is shown in base metal.

6. References