Design Criteria and Lifetime Estimation for the Diffusion Bonded Heat Exchanger of VHTR

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1. Introduction

In order to enhance the compactness and the economics of the advanced reactor, the compact heat exchanger is a potential candidate for the primary heat exchanger and/or steam generator of the reactor system. The photo-chemically etched plates are stacked and diffusion bonded to form the effective heat transfer region of the compact heat exchanger. However, failure modes of the diffusion bonded heat exchanger are not well defined. The design methodology and design criteria for the diffusion bonded area are shortly prescribed in ASME Section VIII but not in ASME Section III [1]. In this study, failure modes of diffusion bonded compact heat exchanger are investigated. The strength reduction factor caused by diffusion bonding is also discussed. The lifetime for the effective heat transfer region of the diffusion bonded heat exchanger is estimated by applying the strength reduction factor of diffusion bonding. Except for the lifetime estimation based on static strength, the fatigue failure and/or the creep failure are important to define the lifetime of diffusion bonded compact heat exchanger. Material tests are being carried out to investigate the effect of diffusion bonding on the creep strength and fatigue strength at elevated temperature until 2022. After characterizing the fatigue and the creep behavior of the diffusion bonded region based on material test results, the lifetime estimation analysis on the fatigue and creep failure will be done in sequence.

2. Lifetime Calculation

In this section, the lifetime calculation procedure for the high temperature reactor component is suggested tentatively.

2.1 Possible Failure Mode

The failure of the diffusion bonded heat exchanger is classified into three basic catago1ies based upon the consequence of failure. The failure of the primary coolant boundary and the failure of the secondary coolant are important to the safety and the performance of the heat exchanger. The failure between primary coolant channels or the failure between secondary coolant channels do not have a significant influence on the structural integrity but reduce the performance of the heat exchanger. Fig. 1 shows the failure across the pressure boundary and the failure between same coolant channels

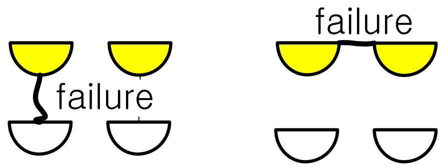

Fig. 1 Typical failure modes in diffusion bonded HX

2.2 Design Criteria

According to ASME section VIII [2], the membrane stress across the thickness S_m should be less than allowable stress of ASME Section II Part D [3]. Also, total stress S_T should be less than 150% of allowable stress. The joint efficiency of diffusion bonding is 0.7 along the diffusion bonded direction. According to ASME Sec. III division 5 in which high temperature reactor component design methodology is specified, the membrane stress P_m, bending stress P_b, local stress P_L, and thermal stress Q are calculated based on stress linearization technique to estimate lifetime at elevated temperature. The aforementioned ASME stress indices and deformation should not exceed the allowable limit of ASME during the lifetime of component.

The strength reduction factor is not defined for Smt up to now [4]. Design stress intensity Smt for the base metal and diffusion bonded region is plotted in Fig. 2.

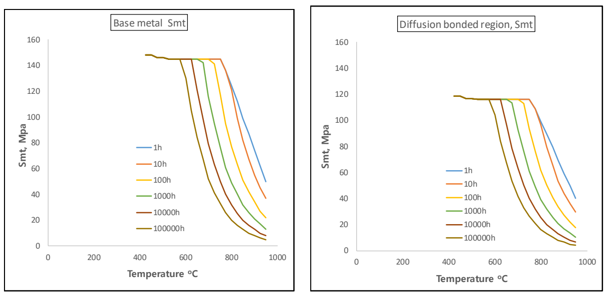

Fig. 2. Allowable limit of general membrane stress for base metal and diffusion bonded metal.

2.3 Lifetime estimation based on static strength

Finite element analysis has been done to obtain linearized stress component for effective heat transfer region.

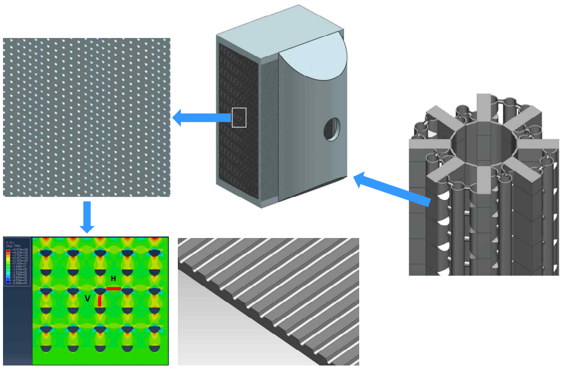

Fig. 3. Effective heat transfer region for analysis

Commercial finite element program ABAQUS is used to obtain the stress distribution [5]. Two loading cases are analyzed. In the first loading case, the primary coolant channel is pressurized and secondary coolant channel is not pressurized. The failure in vertical direction denoted as 'V' in Fig. 3 means failure between primary coolant channel and secondary channel as shown in Fig.3. The failure along horizontal direction denoted as 'H' is failure between primary coolant channels. Stress distributions along the vertical pitch and horizontal pitch are shown in Fig.4

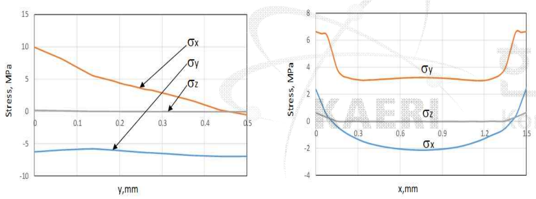

Fig. 4. Stress distributions along the ligament

Lifetime which is estimated from static strength and tentative reduction factor for the effective heat transfer region is shown in Table 1. If ASME code is applied to estimate lifetime of the component made of alloy 617, lifetime can be calculated up to 100,000hours since the allowable stress intensity specified less than 100,000hours in alloy 617 code case. An extrapolated lifetime is suggested for diffusion bonded region in Table 1 for the rough estimations beyond 100,000hours.

Table 1 Lifetime estimation for diffusion bonded region by static strength

Modelling	Section	ASME A617 limit(10^5hr)		Extrapolation	
		Lifetime by membrane stress	Lifetime by total stress	Lifetime by membrane stress	Lifetime by total stress
Primary pressure	V	$>10^5$	23,700	162,897	23,700
	H	$>10^5$	10^5이상	146,845	133,899
Primary and secondary pressure	V	$>10^5$	10^5이상	280,839	209,218
	H	$>10^5$	10^5이상	168,944	153,871

3. Conclusions

The static strength reduction values are studied for the diffusion bonded region. Although PCHE is designed according to ASME Section VIII, the lifetime of PCHE could be evaluated tentatively by using of the ASME Sec. III Div.5 and alloy 617 code case to guarantee structural integrity. Comparative evaluation for the static strength of diffusion bonding at elevated temperature is the prerequisite for the lifetime estimation of diffusion bonded high temperature component. As for further research, the lifetime estimation on the fatigue and creep failure will be done after finishing the material test for the diffusion bonded region.

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[2] ASME, ASME Boiler and Pressure Vessel Code Section VIII, Division 1, 2019

[3] ASME, ASME Boiler and Pressure Vessel Code Section II, Part D, 2019

[4] ASME, code case N-898, Use of Alloy 617(UNS N06617) for Class A Elevated Temperature Service Construction, Oct. 2019

[5] ABAQUS/CAE 6.13-4