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Alloy 617 for the High Temperature Diffusion-Bonded Compact Heat Exchangers

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Abstract – *Driven by the operation conditions which involve high temperature and effectiveness, low pressure drop and relatively low alloy design stress levels, heat exchangers for the next generation of nuclear reactors need to be compact with high integrity construction. It has been demonstrated that the features and characteristics of a diffusion bonded heat exchanger, such as Heatric's Print Circuit Heat Exchanger (PCHE), Formed Plate Heat Exchanger (FPHE) and Hybrid Heat Exchanger, are able to meet the above requirements.*

One of the main challenges for such a compact exchanger is material, which needs to withstand the high temperature exposure for up to 60 years under a very corrosive environment. This requires materials to have good thermal stability, mechanical properties and corrosion resistance. Work on material selection suggests that Inconel alloy 617 is the leading candidate material for the high temperature exchangers.

This paper describes the microstructure and mechanical properties of alloy 617 associated with the high temperature applications. The paper also considers the challenges associated with heat exchanger mechanical design at elevated temperature. It then focuses on the results from Heatric's alloy 617 development programme. These results include the characterisation of as-received material, microstructural examination after diffusion bonding and mechanical testing. A demonstration PCHE core using alloy 617 has been successfully manufactured and has achieved the industry standard leak-tightness.

I. INTRODUCTION

The growing world energy demand, together with considerations of energy security and concerns about greenhouse gas emissions have resulted in a number of national and international programmes to develop advanced nuclear reactors such as the "Generation IV" reactors. Apart from a sustained electricity production, there is a need to produce hydrogen and high temperature heat for industrial processes. This promotes an interest in high temperature heat exchangers, one of the key components in high temperature reactors.

Of the currently available technologies, it has been demonstrated that the diffusion bonded compact heat exchangers such as Heatric's Printed Circuit Heat Exchanger (PCHE), Formed Plate Heat Exchanger (FPHE) and Hybrid Heat Exchanger, are able to meet the requirements.[1] The benefits of these heat exchangers include space and weight saving, high thermal effectiveness, low pressure drop and high design pressure capability.

The material's challenges for the above diffusion bonded-heat exchangers are:

- Materials will be exposed to high temperatures, up to 1000°C. This will generally result in metallurgical structural changes, which may cause strength loss.

- Materials will be exposed to corrosive environments. Even for the helium cooled exchangers, the coolant will be contaminated and may contain N_2, CO, CO_2, H_2, CH_4, and H_2O impurities. The main corrosion reactions may involve oxidation, carburisation or decarburisation depending on the exposure time, temperature, carbon activity in the gas phase, oxygen partial pressure and alloy composition.[2]

- Up to a 60-year operation life will be required. This necessitates very long-term materials stability.

- Process-heat for large-scale hydrogen production will also need materials compatibility with heat transfer media and reactants.

- The ASME design rules associated with creep-fatigue and intermediate heat exchanger at high temperatures are under development.

A suitable alloy for the heat exchangers should have good heat transfer properties. In addition to this, good resistance to corrosion, creep, creep fatigue as well as adequate mechanical properties are required. Inconel alloy 617 has been shown to be the leading candidate material for the high temperature exchangers.[3]

This paper outlines the properties of alloy 617 associated with high temperature applications. The focus is on the results from Heatric's alloy 617 development programme for the diffusion bonded compact heat exchangers.

II. PROPERTIES OF ALLOY 617

Alloy 617 (UNS N06617) is a solid-solution, nickel-chromium-cobalt-molybdenum alloy with a good combination of metallurgical stability, strength, and oxidation resistance at high temperatures. The alloy also has excellent resistance to a wide range of corrosive environment and it is readily formed and welded by conventional techniques.

The cobalt content of alloy 617 is between 10 and 15 wt%. The activation of this element could result in long term radioactivity if the material is submitted to a significant fluence. Considering that the radioactivity in high temperature gas cooled reactor is much lower than that in pressurized water reactor and high temperature heat exchangers are normally located outside of the reactor vessel, the effect of cobalt will be limited.

The critical factors affecting materials properties are associated with their microstructures such as the phases and their amount existing in the materials. The major phase present in this alloy is a FCC matrix and a small amount of carbides. This alloy does not exhibit significant intermetallic phase formation, such as sigma phase at high temperature. Such alloys normally exhibit good ductility, even after long-term thermal exposure to high temperatures.

The design of high temperature heat exchangers will be influenced by the alloy's physical properties especially thermal conductivity and thermal expansion. Temperature changes within heat exchangers under transient conditions such as start-up and shut-down can generate thermal stresses which may eventually initiate and propagate fatigue cracks. These thermal stresses are generally proportional to the alloy's thermal expansion coefficients. A suitable heat exchanger material should have a high thermal conductivity and low rate of thermal expansion.

When compared with other high temperature metallic materials, Alloy 617 shows a good combination of thermal conductivity and thermal expansion coefficient.[3] Typical values at 1000°C are given in the Table below:

TABLE I

Comparison of Thermal Conductivity and Thermal Expansion for High Temperature Alloys at 1000°C

	Thermal Conductivity (W/mK)	Coefficient of Expansion (µm/m°C)
Alloy HX	27.9	16.7
Alloy 230	28.4	16.1
Alloy 617	28.7	16.3

According to ASME VIII-Div.1, alloy 617 is approved for applications at temperatures up to 982°C. Fig.1 shows the maximum allowable stresses of this alloy against temperature. As expected, the strength of this alloy decreases with increasing temperature.

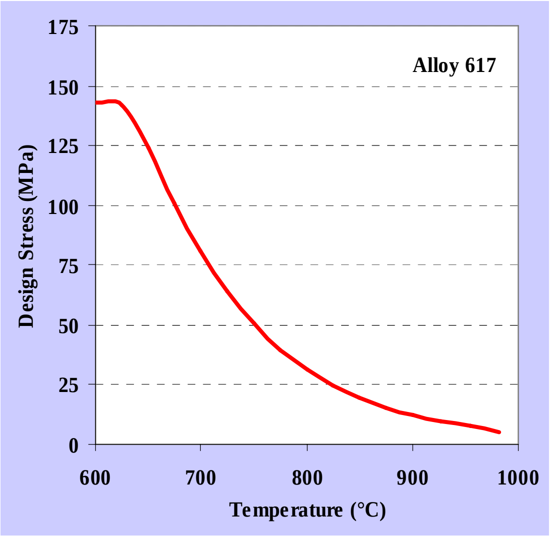

Fig. 1. Maximum allowable stresses of alloy 617.

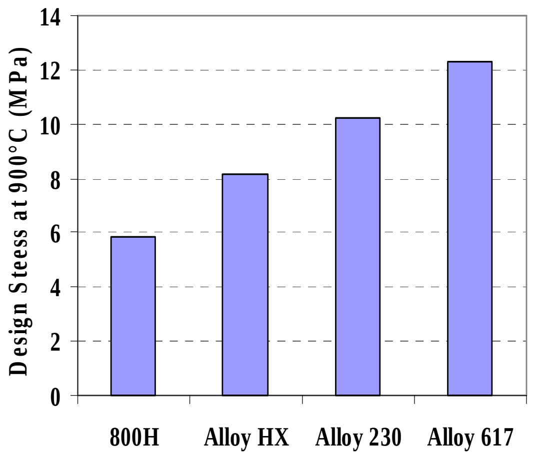

Fig. 2. Comparison of maximum allowable stress at 900°C.

The design stresses in Fig. 1 assume design to ASME VIII, they are based on a creep life of 100,000 hours (about 11 years) at temperatures above 825°C.[4] When exposed to high temperatures under a certain stress, materials are susceptible to a time-dependent deformation called creep. This phenomenon is accelerated with increasing temperature and stress level. As 100,000 hours is much shorter than the required heat exchanger design life (30 to 60 years), consideration should be given to design stresses lower than those reported in Fig. 1 or reduced design life.

As a heat exchanger normally contains certain pressure, it must have significant strength at temperature. Compared with other candidate materials such as alloy 800H (UNS N08810), alloy HX (UNS N0602), alloy 230 (UNS N06230), alloy 617 has the highest design stress at 900°C (Fig. 2). The value is 12.3MPa,[3] which is about two times of the value for alloy 800H.

The environmental effects on material properties need to be considered. High temperature interaction of alloy 617 with impure helium can result in bulk carburization, decarburization and/or oxidation depending upon helium gas chemistry, exposure time, alloy composition and temperature.[5,6,7,8] At a given temperature, the activity of carbon (carburization potential) and partial pressure of oxygen (oxidation potential) determine the types of interaction.[2]

III. DIFFUSION BONDED HEAT EXCHANGERS

This section focus on the results from Heatric's alloy 617 development programme on diffusion bonded compact heat exchangers. These results include microstructural characterization and mechanical properties in both as-received and post-bonding conditions.

III.A. As-Received Alloy 617

The alloy 617 was received in sheet form and a typical composition is given in Table II.

TABLE II

Normal Composition of As-Received Alloy 617

Ni	Cr	Co	Mo	Fe	Mn
Bal.	21.5	12.2	9.3	0.3	0.1
Al	Ti	C	Cu	Si	B (ppm)
0.9	0.4	0.06	0.01	0.08	<10

Typical Mechanical properties for as-received alloy are 770 MPa for ultimate tensile strength, 340 MPa for 0.2% Proof strength and 60% for elongation.

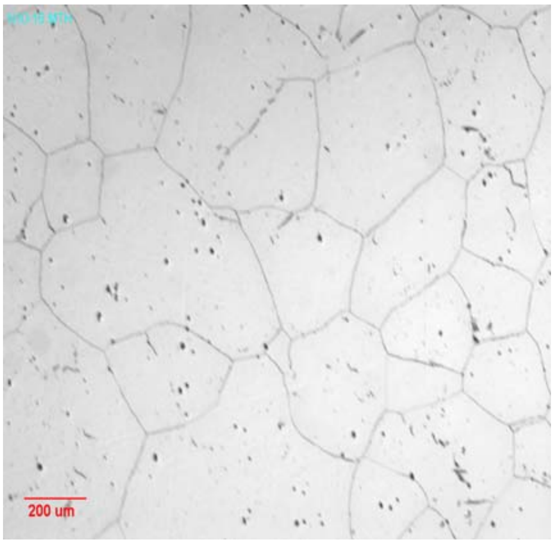

Fig. 3. Micrograph of as received alloy 617.

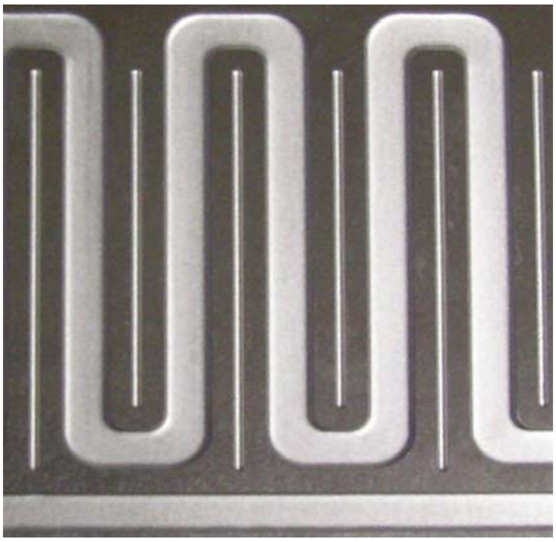

Fig. 4. Channel formation by chemical machining.

Microstructure for as-received alloy 617 is shown in Fig. 3. Apart from the FCC matrix phase, it shows the presence of small amounts of carbides.

III.B. Diffusion bonding alloy 617 heat exchangers

The key technologies for diffusion bonded heat exchangers are channel formation and diffusion bonding. The fluid flow passages in alloy 617 plates can be manufactured by photo chemical machining, electrochemical machining or fin forming. Selection of the appropriate passage forming technology is dependent upon the heat exchanger characteristics and cost. Fig. 4 shows the channel formation on a 617 plate using photo-chemically machining method.

Diffusion bonding is a "solid-state joining" process involving pressing metal surfaces together at temperatures below the melting point, therefore promoting grain growth between the surfaces. A typical micrograph for diffusion bonded alloy 617 is given in Fig. 5, which shows grain growth across the bond line.

The process of diffusion bonding is dependent on a number of proprietary parameters, including time, pressure and temperature.[9] Under carefully controlled conditions, diffusion-bonded joints reach parent metal strength.

Fig. 5. Micrograph of alloy 617 showing grain growth across the joint interface.

After diffusion bonding process, bend tests were carried out to ensure that the bonds have sufficient ductility to stand bending without fracturing. A typical bend test specimen for the diffusion-bonded alloy 617 is shown in Fig. 6, which demonstrates no cracks and good ductility.

Fig. 6. Bend test for diffusion bonded alloy 617.

Fig. 8. Tensile sample for diffusion bonded alloy 617 showing necked region.

Tensile tests at room temperature (RT) and elevated temperatures were also performed to measure the 0.2% proof strength (0.2%PS), ultimate tensile strength (UTS) and elongation to failure. The direction of the tests was perpendicular to the bonded plates. A typical fracture surface of a tensile test sample indicates a bond much closer to base material, with significant cup and cone formation (Fig. 7). No bond line appears to have influenced the location of fracture on a macroscopic level and significant necking of the sample occurs (Fig. 8).

Fig. 7. Fracture surface of a diffusion bonded alloy 617 tensile sample showing cup-and-cone fracture.

The strength and deformation values for diffusion bonded alloy 617 at room temperature are 0.2% PS of 334MPa, UTS of 696 MPa and elongation of 52% (Table III). The results met the ASME requirements, which are 240MPa for 0.2% proof strength, 655MPa for UTS and 30% for the elongation.

TABLE III

Tensile Test Results for Diffusion Bonded Alloy 617

Temp (°C)	0.2%PS (MPa)	UTS (MPa)	EL %
RT	334	696	52
950	106	182	54

The maximum allowable design stress of alloy 617 at 950°C is based on 100,000 hours of design life. Thus the comparison between the short time mechanical properties and the ASME requirements is not straightforward. Nevertheless, the average 0.2% proof strength achieved at 950°C was 106 MPa (Table III), which is about 13 times higher than the design stress at this temperature (7.91 MPa). Good ductility was also observed with the average elongation of 54% (Table III).

Feedback from our customers regarding the mechanical test results for our supplied diffusion-bonded alloy 617 test coupon is satisfactory.

A demonstration diffusion bonded alloy 617 heat exchanger has been manufactured. The etched plate and cross-section is demonstrated in Fig. 9. Helium leak testing was performed and the core has achieved a leak rate of 8.6E-9 mbar l/sec. This value exceeds the requirements for our diffusion bonded heat exchangers.

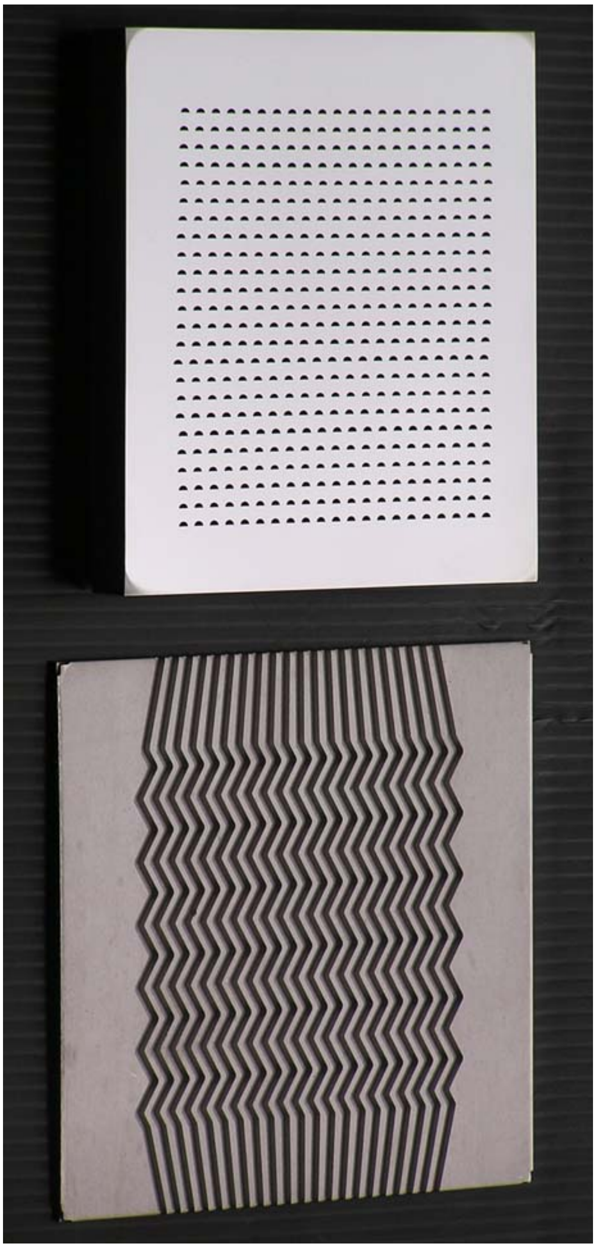

Fig. 9. Etched plate and cross-section of diffusion bonded alloy 617 heat exchanger.

IV. CONCLUSIONS

1) Inconel alloy 617 is being suggested as the most suitable material for high temperature diffusion bonded compact heat exchangers.

2) Heatric has successfully developed a heat exchanger fabrication technique, including the formation of fluid flow passages and diffusion bonding in alloy 617.

3) The mechanical properties of the diffusion bonded alloy 617 met the ASME requirements.

4) The diffusion bonded alloy 617 heat exchanger core achieved a leak-tightness of 8.6E-9 mbar l/sec.

5) The characteristics of Heatric’s diffusion bonded compact heat exchangers are fully developed, commercially available and capable of meeting the heat exchange requirements of the next generation of nuclear reactor.

6) Further work associated with high temperature time dependent properties and the effects of environment is required. The design rules for high temperature heat exchangers also need to be established and developed to meet the requirements of the next generation of nuclear reactors.

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