Manufacturing Technology of Diffusion-bonded Compact Heat Exchanger (DCHE)

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The Diffusion-bonded Compact Heat Exchanger (DCHE) is a compact heat exchanger, and the demand for it is expected to increase in applications for weight saving or those calling for a compact plot area, as well as for use in floating plants. Kobe Steel has been working on the development and establishment of the manufacturing technology of DCHE, which is a compact and high strength micro channel heat exchanger. Its heat transfer performance has been evaluated by comparing it with the conventional shell & tube type heat exchanger, and its strength and fatigue have been evaluated using Kobe Steel's stress analysis technology and fatigue test. This paper introduces the features of DCHE and the activity involved in its development.

Introduction

The number of marine resource projects that require equipment with a small footprint and high efficiency is increasing. Thus, high-efficiency compact heat exchangers designed for floating plants are gathering increasing attention. These compact heat exchangers include microchannel heat exchangers with flow passages, each several millimeters in size, to ensure a large heat transfer area per unit volume.[1)] Such microchannel heat exchangers can be made small in size and will contribute to weight reduction.

Kobe Steel has over 40 years of experience in delivering brazed aluminum plate-fin heat exchangers (hereinafter, ALEXs®[note)]). Adapting their design and manufacturing technologies,[2)] the company has developed a diffusion-bonded compact heat exchanger (hereinafter DCHE).

This paper introduces the structure and features of DCHEs and reports the verification results for their heat transfer performance and mechanical strength.

1. Structure and features of DCHE

1.1 Structure of DCHE (comparison between ALEX and DCHE)

An ALEX comprises a brazed core body for exchanging heat and a header/nozzle for guiding fluid inside the core (**Fig. 1**). The core body includes multiple assemblies, each consisting of a parting sheet, fin and side bar (**Fig. 2**), which are cut out in the required sizes. These assemblies are stacked and brazed together in a vacuum furnace to constitute the core body. To ensure sound brazing and weight reduction, aluminum alloy is used as the material.

The production process of a DCHE is shown in **Fig. 3**. A DCHE has a stacked structure similar to that of an ALEX and is produced in almost the same manner, but with some significant differences in the flow-passage fabrication and joining. The flow passages of a DCHE are fabricated by chemical etching done directly on the material plates, rather than by fin forming. Thus each layer consists of only one plate, which facilitates assembly by stacking.

The joining is accomplished by diffusion bonding, which can offer stronger joints than brazing. The plate material depends on the application. For example, stainless steel, having a strength and corrosion resistance higher than those of aluminum alloy, is used for applications in which an ALEX cannot be used.

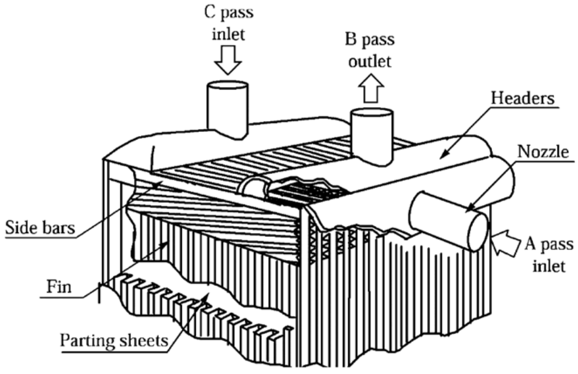


Fig. 1 Structure image of ALEX

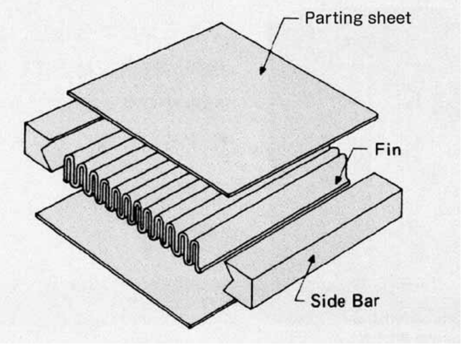


Fig. 2 Main parts of ALEX

[note)] ALEX is a registered trademark of Kobe Steel.

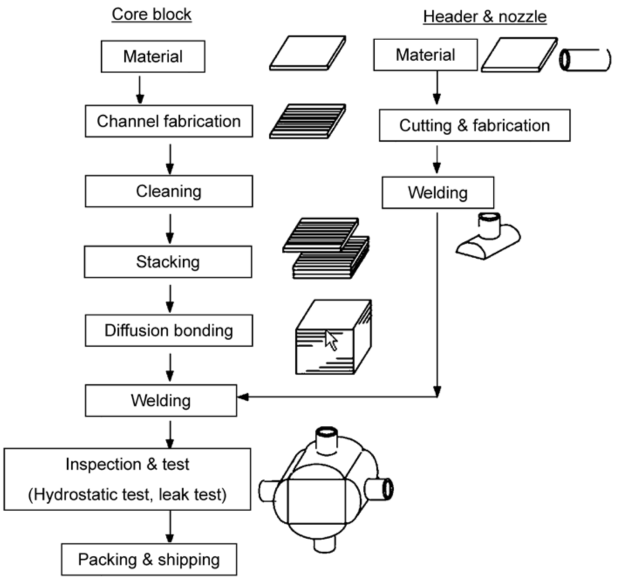


Fig. 3 Manufacturing flow of DCHE

1.2 Advantages of DCHE

A DCHE is based on the design and production technologies of the ALEX and has the advantage of possessing the capability of exchanging heat among several fluids at a time.[3)] **Fig. 4** schematically shows an example in which three fluids are involved. As shown, optimizing the design for the flow passage of each fluid in accordance with its processing conditions permits one heat exchanger to exchange heat among several fluids. This makes it possible to unify a number of multitubular heat exchangers.

Several materials, including stainless steel, nickel-base alloy and titanium, have so far been evaluated for their flow-passage fabrication and bonding performance. The use of stainless steel enables the flow passages to be made several millimeters in size with thin walls, thanks to its high strength. As a result, excellent heat-transfer performance is expected even when stainless steel is used, in spite of its relatively poor thermal conductivity.

Furthermore, diffusion bonding ensures a joining strength higher than that achieved by brazing, making it possible to use the DCHE in applications to which ALEX has been inapplicable: for example, applications involving high pressure (13MPa or higher) and/or with operational fluctuations.

1.3 Applications of DCHE

A DCHE is a heat exchanger that can handle several fluids at a time and is used, depending on its material and the size of its flow passage, up to the designed pressure of 100MPa and design temperature of 900℃. The following describes possible applications:

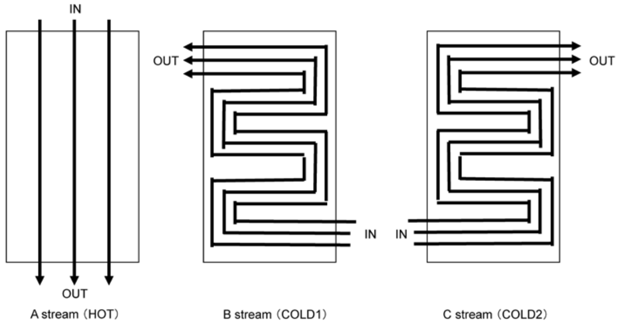


Fig. 4 Stream images of multi pass (3 stream examples)

(1) Equipment requiring compactness, such as offshore facilities
Example: Intercoolers and aftercoolers for compressors
(2) Equipment installed at a height, requiring compactness and lightness
Example: Vaporizers and condensers used on towers such as distilling columns
(3) Applications with severe operating conditions (e.g., high pressure, large temperature differences among fluids, operational fluctuations)
Example: Hydrogen coolers for high-pressure hydrogen stations

It should be noted that, from the aspect of economy, the ALEX is recommended for applications in which the design pressure is low enough (13MPa or lower) and there are no operational fluctuations.

2. Verification of heat transfer performance

2.1 Technique for performance calculation

The performance calculation of a DCHE employs the calculation technique used for the ALEX, which has already been proven in many applications. More specifically, regarding the fin shape of an ALEX as the flow passage shape of a DCHE, as shown in **Fig. 5**, enables us to apply the design techniques of ALEX. This conversion from the ALEX to DCHE is applicable also to the strength calculation for each member.

The detailed calculation of the pressure loss and heat transfer performance requires coefficients (dimensionless numbers). These coefficients are obtained by making small cores, each simulating a corresponding flow passage, and measuring their pressure loss and heat transfer performance. The results are reflected in the performance calculation.

2.2 Performance verification test

To verify the performance calculation technique

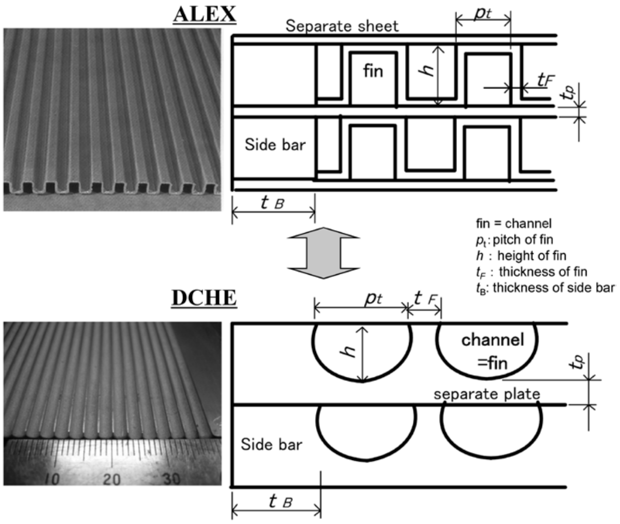
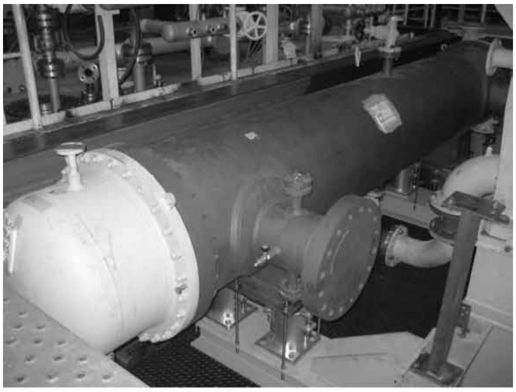
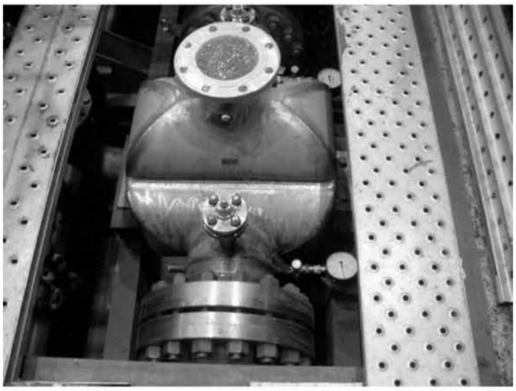


Fig. 5 Relationship of form between ALEX fin and DCHE channel



(a) Shell & Tube
Φ650 × 4,200TL-TL (5,500kg)



(b) DCHE
330 × 350 × 650 (700kg)

Fig. 6 Outside view of Shell & Tube and DCHE at same condition

and to confirm the performance, a DCHE was adapted to the aftercooler of a compressor. **Fig. 6**-top shows a multitubular heat exchanger, which has conventionally been used for the aftercooler of a compressor having a design pressure of 9MPaG. This multitubular heat exchanger is replaced by a DCHE (Fig. 6-bottom), designed for similar conditions of heat transfer performance and pressure loss, to measure the DCHE's pressure loss and heat transfer performance.

Each of these heat exchangers was operated under various conditions to confirm its performance. The results have demonstrated that the DCHE performs with heat transfer and pressure loss as designed. This verifies that the design, based on the design technique for the ALEX, is applicable to the DCHE. Also, it has been demonstrated that a DCHE can be made significantly compact, approximately 1/10 in volume and 1/8 in weight, compared with the multitubular heat exchanger with the same heat transfer performance and pressure loss. It should be noted that greater effects than those of the conventional heat exchanger are achieved in compactness and weight reduction in cases where the operating pressure is higher and/or where a higher heat transfer performance is required.

3. Verification of mechanical strength of diffusion-bonded bonding parts

3.1 Diffusion bonding

Diffusion bonding is a key step in producing a DCHE. Diffusion bonding is defined in JIS Z3001[4] as "a method for joining comprising the steps of closely sticking base materials together and pressing these materials against each other at a temperature not exceeding their melting points, while suppressing their plastic deformation to a minimum, so as to cause the diffusion of atoms at the joining interface to complete the bonding." It is considered to falls into the category of solid phase joining, which includes various other pressure welding methods such as friction welding and cold pressure welding (ambient temperature pressure welding).[5, 6] **Fig. 7** shows an example of the results of cross-sectional observation on a diffusion-bonded product.

In a DCHE, several hundreds of plates are stacked, each having flow passages. The stacked plates must be homogeneously bonded together to achieve the heat transfer and pressure resistance required. Thus, verification by a bonding test becomes just as important as, for example, theoretical verification obtained by analysis.

3.2 Compliance with regulations and standards

DCHEs handle high-pressure gas and liquefied gas in many cases. In those cases, they must comply with the "High Pressure Gas Safety Law" in Japan and the "Boiler and Pressure Vessel Code (BPVC)" of the American Society of Mechanical Engineers

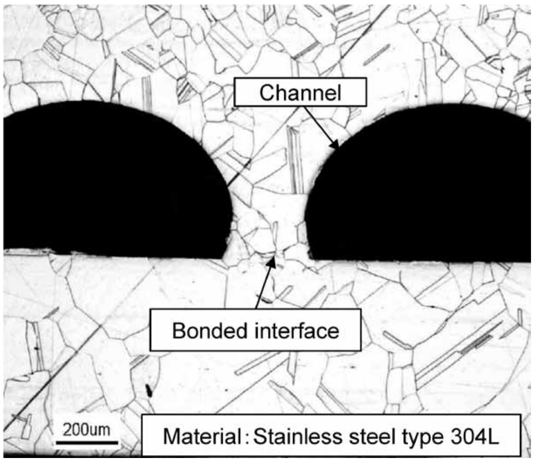


Fig. 7 Channel and cross-section observation of diffusion bonding

(ASME) outside Japan. **Fig. 8** shows an example of products that have passed testing according to the ASME standard. The soundness of each product is assured by its passing the non-destructive test, hydrostatic test and air tight test (leak test) required by the standards. Thus, advance verification of the diffusion bonding technique is indispensable. As in the case of the ALEX, the bondability is evaluated on the following points:

① Soundness evaluation for diffusion-bonded bonding parts (bondability attributable to materials)
② Strength evaluation for flow passage shape (bondability attributable to shapes)

The following sections describe the verification results for each item.

3.2.1 Soundness evaluation of diffusion-bonded parts

The details of the bonding method used in each product are determined and managed for the corresponding material by "diffusion bonding procedure qualification records (DPQRs)." When evaluating soundness, samples are prepared in accordance with each DPQR. The test pieces taken from these samples were evaluated for their mechanical properties. As a result, it has been confirmed that the bonding parts exhibit tensile strength, proof strength and elongation, all equaling or exceeding the standard value, regardless of the bonding location (the positions where the specimens were taken) and direction (vertical or parallel to the bonding interface).

3.2.2 Strength evaluation focusing on the flow passage shape

As described above, the bonding conditions are determined on the basis of the DPQR. In general, the shapes of flow passages determine the strength of an entire heat exchanger regardless of the material and bonding conditions. Therefore, the strength in relation to the flow passage shape is evaluated not only by calculation, but also by a burst test conducted on test samples. In a burst test, a diffusion-bonded test sample is pressurized by water, or by oil, and the pressure is measured when a part of the test sample starts to crack. The burst pressure is determined rather easily because the flow passage, unable to take any more pressure, expands, increasing its inner volume and causing the inner pressure to drop rapidly.

Fig. 8 DCHE with U-stamp of ASME

As an example of the burst test, a sample made of SUS316L stainless steel was tested. The result has confirmed that the test sample, with its flow passage shaped for high pressure, withstands a pressure of 450MPa or higher. Adopting a safety factor of 4 for this flow passage shape makes the design pressure 100MPa or higher. Different types of flow passages were subjected to bursting tests, which yielded bursting pressures that fall within plus/minus several percentages of variation, verifying the stability of the bonded parts.

4. Verification of fatigue strength

Applications for DCHEs include heat exchangers for high-pressure hydrogen stations. Conventionally, double-pipe heat exchangers have been used for this application because it calls for water cooling ultra-high-pressure hydrogen of approximately 80MPa. The problem with these conventional heat exchangers was that a great many number of joints are involved, and the equipment is large in size. In particular, a hydrogen station is expected to be annexed to an existing filling station and is required to be small.

The following are the specific applications of DCHEs for hydrogen stations:

① Intercoolers and aftercoolers of compressors (design pressure 95MPa, design temperature not exceeding 180℃)
② Precoolers for dispensers (design pressure 92MPa, design temperature –50℃ to 50℃)

These applications require not only the static mechanical strength, but also the fatigue strength to withstand daily start-stop operation and the pressure fluctuations of the compressors. Therefore, an evaluation of strength was conducted by analysis under the following conditions (Test 1 and Test 2). A fatigue test was also performed using a test sample that simulated an actual heat exchanger in a high-pressure environment, as shown in **Table 1**. The results were used to verify the mechanical strength. Here, Test 1 assumes a cooler for the compressor in accordance with application ①, while Test 2 assumes a precooler for the dispenser in accordance with application ②.

4.1 Evaluation by stress analysis

Fig. 9 depicts an analysis model for the flow passage shape of the present heat exchanger. **Fig.10** depicts the result of an analysis of the model in operation. Values required for fatigue strength evaluation, such as peak stress, mean stress, and stress amplitude of pressure fluctuations were calculated on the basis of the peak stress measured at a corner of each flow passage. The fatigue strength was evaluated on the basis of the design fatigue curve with the mean stress corrected for austenitic stainless steel. The results have confirmed that there is sufficient margin in the operating conditions and no problem in the use.

Table 1 Pressure fluctuation condition

	Test 1	Test 2
Test media	Water	Hydrogen
Temperature of test device	20℃	-40℃
Range of pressure fluctuation	86.5MPa	90MPa
Cycle of pressure fluctuation	100,000 cycle	70,000 cycle

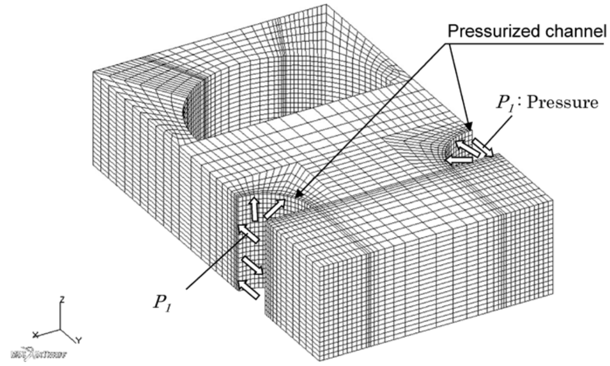


Fig. 9 Stress analysis model

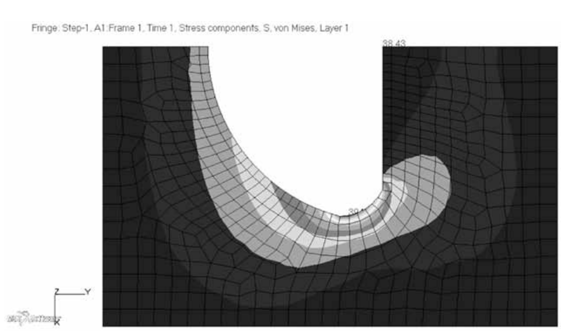


Fig.10 Stress analysis of production simulation model

4.2 Evaluation by fatigue test

Cycle tests under varying pressure, shown in Table 1, were conducted as shown in **Figs.11** and **12**. Neither test resulted in bursting of the test sample even after the planned number of cycles was exceeded. No leak of fluid (water or hydrogen) was detected, either. After the pressure cycle test, a tightness leak test using helium as the test fluid was performed to reconfirm that there was no leakage from any spot. These results verify the validity of the analysis and fatigue strength evaluation technique described above.

Furthermore, the diffusion-bonded parts were evaluated for hydrogen embrittlement. Specimens taken from the diffusion-bonded test samples were hydrogen charged and subsequently subjected to a tensile test at a low strain rate. The results confirm

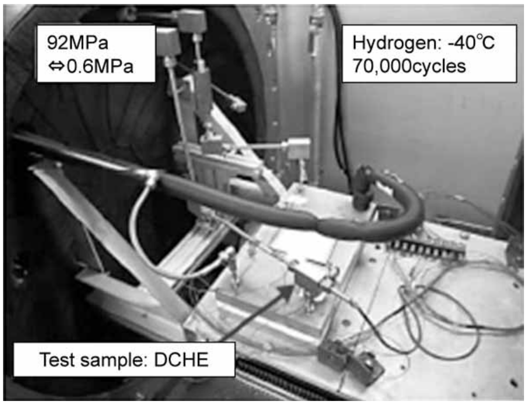


Fig.11 Cycle test of pressure fluctuation（Test 2）

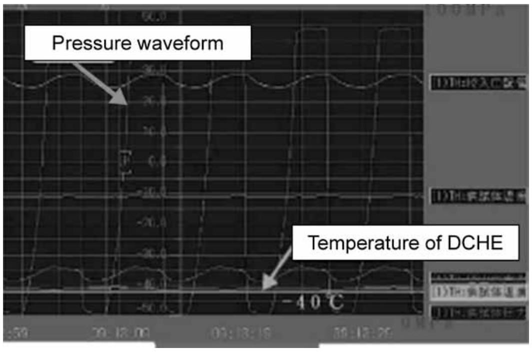


Fig.12 Cycle test of pressure fluctuation（Test 2）

that no effect of embrittlement is recognized in a high-pressure hydrogen environment.

From the above, the diffusion-bonded product has been confirmed to pose no problem in bonding quality and it has been found to withstand the pressure cycle test that accounts for the start-stop operation of a hydrogen station.

On the basis of these results, an aftercooler for a hydrogen compressor, shown in **Fig.13**, was fabricated in accordance with the designated equipment inspection regulations of the high pressure gas safety law. The equipment is very small, being only 1/30 to 1/100 the size of the conventional double-pipe heat exchanger. The DCHE is expected to be used in a variety of applications.

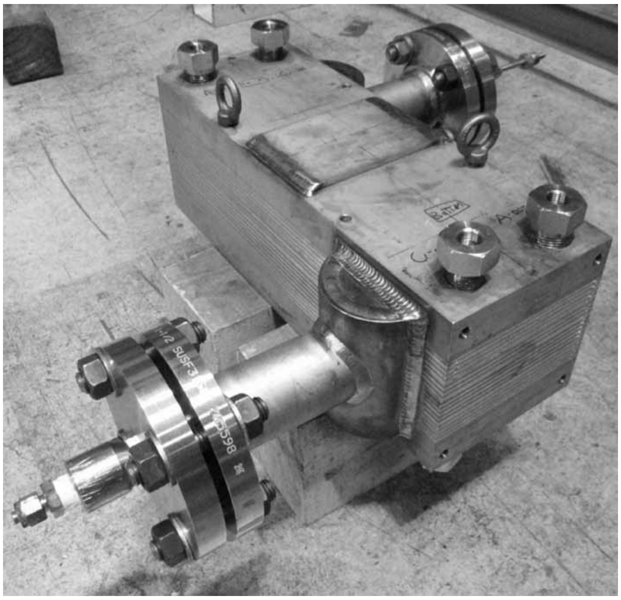


Fig.13 Outside view of DCHE for hydrogen station

Conclusions

This paper introduces the diffusion-bonded compact heat exchanger (DCHE), a type of compact heat exchanger. The diffusion-bonding technique has been confirmed to pose no problem in bonding quality, which has been verified by mechanical testing and fatigue testing, as well as by computer analysis. The applications for DCHEs are expected to increase as they are used for hydrogen stations, a high-pressure application in which reliability counts most. Meanwhile, for offshore applications, DCHEs should be larger in capacity, and of high-performance, and their production technologies are being improved. We will continue to accumulate experience in producing DCHEs to further improve their reliability and will continue their development for further applications.

Lastly, we would like to express our gratitude to Tatsuno Corporation for conducting the experiment introduced in Table 1, Test 2.

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