Materials Research Proceedings 38 (2023) 17-21 https://doi.org/10.21741/9781644902837-3

Manufacturing of Compact Heat Exchangers by Hot Isostatic Pressing

Emmanuel Rigal[1,a*], Isabelle Moro-Le Gall[1,b], Matthieu Maunay[1,c], Sébastien Chomette[1,d], Lionel Cachon[2,e], Sébastien Vincent[2,f]

[1]Univ. Grenoble Alpes, CEA, Liten, DTCH, Grenoble, France

[2]CEA DES IRESNE, DTN, Cadarache, Saint-Paul-Lez-Durance, France

[a]emmanuel.rigal@cea.fr, [b]isabelle.moro@cea.fr, [c]matthieu.maunay@cea.fr, [d]sebastien.chomette@cea.fr, [e]lionel.cachon@cea.fr, [f]sebastien.vincent@cea.fr

Keywords: Hot Isostatic Pressing, Diffusion Welding, Compact Heat Exchangers, Modelling

Abstract. Compact plate heat exchangers (CPHE) are made of millimetric grooved plates stacked and joined together. Among joining processes, diffusion welding is the only one that allows joining the core of the modules without filler material (e.g., braze). However, several challenges must be met to achieve such components, including management of deformation of channels, soundness of joints, non destructive controllability and so on. Part of the achievements made in the frame of the development of the sodium-gas heat exchanger modules of the ASTRID prototype of 4th generation nuclear reactors are described in this presentation, focusing on process modeling and experimental validation with 316L steel.

Introduction

Diffusion welding (DFW) is a solid state welding process where pressure is applied at elevated temperature without macroscopic deformation nor relative motion of pieces [1]. DFW can be achieved by HIP or by uniaxial pressing, with significant differences due to the more uniform character of gas pressure compared to compression via rigid plates. Uniaxial pressing is often used for the manufacturing of CPHE, however, large HIP vessels are available worldwide, instead uniaxial presses are scarce and limited in size. The size of the DFW manufacturing equipment is of importance when dealing with CPHE because large modules are needed to benefit at best of compactness (i.e., a heat exchangers made of a great plurality of small modules are less compact), particularly for nuclear applications, which deal with high thermal power.

Some of the achievements made by CEA about manufacturing of CPHE by HIP-DFW are reported in the following. This work has been made in the frame of the development of the sodium – gas heat exchangers for the 4th generation nuclear reactor ASTRID [2] which is now abandoned, however many other advanced concepts are still under consideration [3], as well as Small Modular Reactors and non nuclear applications for hydrogen management, solar receivers and so on.

Issues

Using HIP DFW to manufacture parts with embedded cooling channels is quite common since long, see for example fusion reactor applications (ITER and beyond, [4], [5]) or applications in the field of molds and tools. Cooling channels are mainly achieved using tubes or additively manufactured parts. Seal welding channels ends to the canister allows to HIP DFW the stack of pieces at high pressure, because the pressurizing gas enters the cooling circuit, thereby preventing its collapse. Alternatively, grooved parts are encapsulated under vacuum and pre-welded using low pressure to avoid excessive deformation, then the assembly is consolidated using HIP. This last solution obviously prevails for CPHE. As a consequence, the *control of the deformation of the grooves* during the low pressure DFW step is an important issue.

Decreasing pressure to decrease deformation presents risks in terms of weld soundness. The achievement of *high weld quality* is a second issue.

The choice of a material grade with suitable "diffusion weldability" is the third issue to be solved [6]. The fourth issue is the control of the final grain size. This article deals solely with the two first issues.

Deformation

Figure 1 shows the case of a pair of plates submitted to isostatic pressure. At edges, far from the grooves, the welding stress (that acts perpendicularly to the interface) equals the pressure. At the ribs, it is several folds higher, depending on the dimensions. Two kinds of deformations can be observed: (i) excessive rib compression leading to a barrel shape, (ii) depression of the arch when the value of t is too small. Both types lead to a reduction of h.

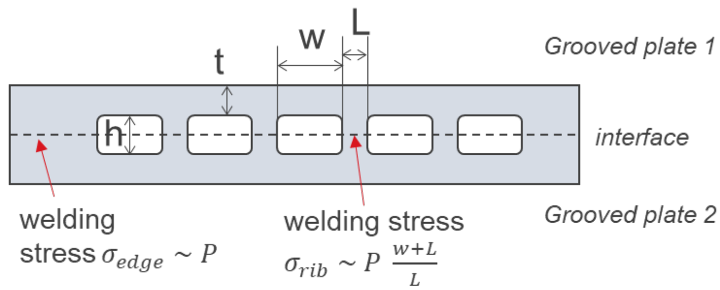


Figure 1: Pair of plates submitted to an isostatic pressure (schematic).

Figure 2 shows experimental results which illustrate deformation. It is seen for example that for this geometry at 60bar, L=2mm is required to avoid shortening of the ribs.

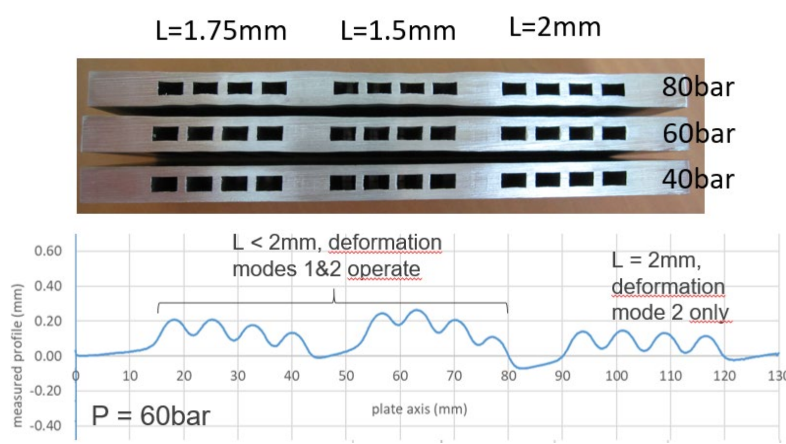


Figure 2: Left: deformation of channels, for 3 pressure values, in pairs of HIP DFWed 316L plates exhibiting 3 series of channels (w=5.75mm, h=3.5mm, t=1.75mm) with different values of L (1.5, 1.75 and 2mm). Right: surface profile showing deformation at 60bar.

The deformation of a stack of plates is more complex because channels tend to shield the welding stress, which distribute unevenly in the stack. This motivates the need for modelling, which is a powerful tool to optimize the HIP cycles and the CPHE geometry. FE modelling has been developed at CEA and has proven to give reasonably accurate results, after optimization of the constitutive law describing the high temperature behaviour of the material, Fig. 3 [7].

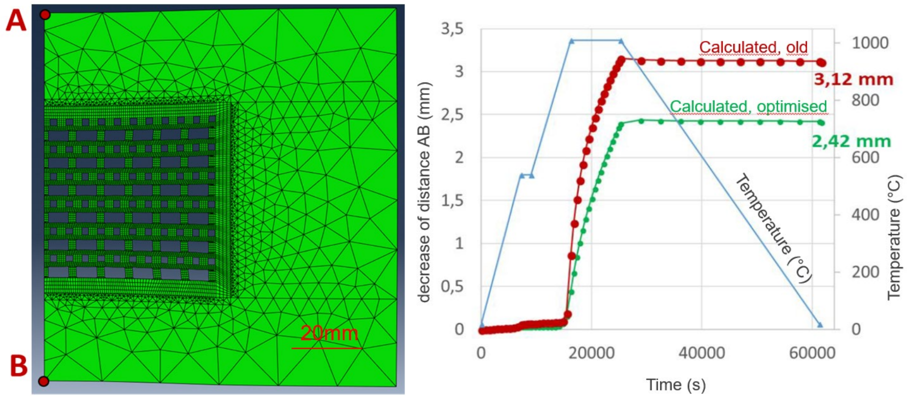
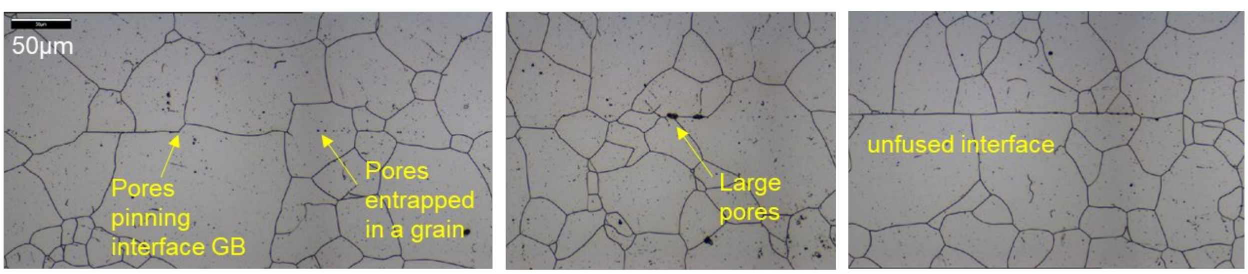
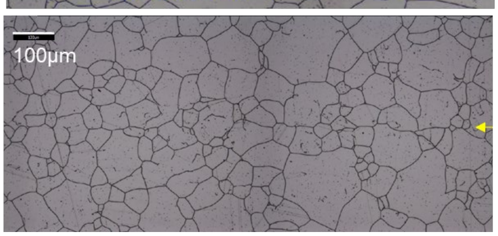


Figure 3: Left: mesh for FE modelling a stack of grooved 316L plates, Right: calculated deformation during the HIP cycle. The experimental value of AB decrease was 2.3mm.

Weld quality

Defects at DFW interfaces can be classified as (1) lack of densification (gaps, pores) and (2) microstructural imperfections (inclusions, contamination particles, uncrossed interface). The latter are not specific to CPHE manufacturing and will not be discussed here. As explained before, the process relies on a combination of low pressure DFW with encapsulated channels and high pressure HIP with open channels. Figure 4 relates to a stack of 4mm thick 316L plates. Interface characteristics are greatly improved by the HIP treatment: pores disappear and zones where the grain boundaries do not cross the interface are greatly reduced. After low pressure DFW, the joints exhibit rupture at one interface with reduced tensile strength and elongation as well as very small impact toughness compared to base material. The mechanical properties of joints largely improve after high pressure HIP, as shown in Table 1.





316L	Low P	+ high P
grain size	34µm	50µm
% crossed interface	63%	85%
pores	yes	no

Figure 4: Top: microstructure of 316L plates DFWed under low pressure. Bottom left: microstructure after high pressure HIP. Bottom right: interface characteristics.

Table 1: Tensile and impact toughness of DFWed 316L plate joints. (*) notch at an interface.

Cond.	Rp0.2% (MPa)	Rm (MPa)	El. (%)	RA (%)	KV (J)*
Low P	220	471 ± 16	24.3 ± 3.5	20.5 ± 3	28-30
+ high P	212	550 ±0.5	83.1 ± 3	62.5 ± 6.5	250-280
Specs.	> 220	> 525	> 45	-	-

Materials Research Proceedings 38 (2023) 17-21 https://doi.org/10.21741/9781644902837-3

Achievements

The ASTRID sodium-gas heat exchanger has a 1500MW thermal power. It involves a flow rate of 7200kg/s nitrogen (180bar pressure) and 6400kg/s Na. Na enters the CPHE at 530°C and leaves it at 345°C (310°C and 515°C for nitrogen).

In the course of the development program, four 40kW mock ups made of 316L grooved plates were manufactured (Fig. 5) and tested. The tests were conducted using a specifically designed loop at CEA/Cadarache. Test involved the injection of 0.2kg/s Na at 530°C and 0.2kg/s nitrogen at 310°C, 80bar (counterflow). One mock up was tested over a one year period, during which it withstood about 800 thermal cycles (120°C/min) and steady state creep at 550°C for 300h, without any signs of heat exchange degradation. Accordingly, expertise of the material showed no joint degradation, however nitride precipitation was noticed, which resulted in hardening of the material and moderate ductility loss (Fig. 6).

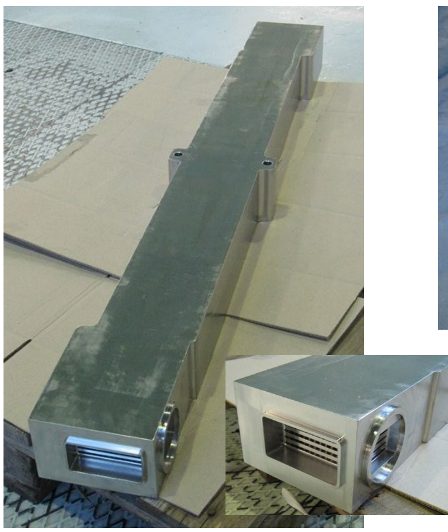
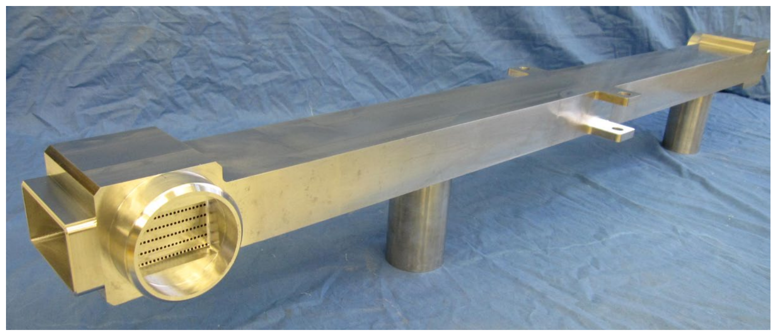
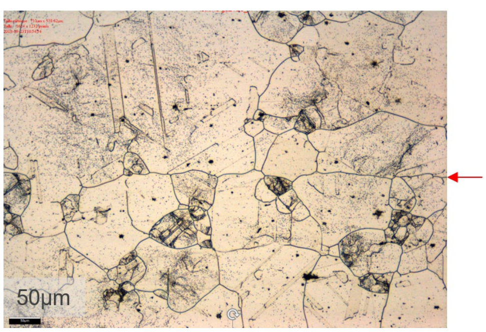



Figure 5: 40kW 316L mockups (1.4m long)
- *6 rows of 12 Na channels, 2x2mm*
- *6 rows of 24 gas channels, 3.5x5.75mm*



Condition	Rp0.2% (MPa)	Rm (MPa)	El. (%)	RA (%)
Before testing	219	557	86	65
After testing	230	557	69	71
specs	> 220	> 525	> 45	-

Figure 6: DFWed 316L after loop testing, showing no degradation but nitride precipitation and hardening

Summary

Compact Plate Heat Exchangers, made of grooved plates, can be diffusion welded by HIP using a combination of a low pressure cycle (vacuumed channels) and a high pressure cycle (open channels) for consolidation. The deformation of the stack can be calculated with reasonable accuracy thanks to finite element modeling. Manufacturing strategies have been developed and applied to test mockups which did not show degradation after loop testing under relevant conditions.

References

[1] Standard Welding Terms and Definitions, AWS standard A3.0M/A3.0:2010, American Welding Society, 2010

Materials Research Proceedings 38 (2023) 17-21 https://doi.org/10.21741/9781644902837-3

[2] L. Cachon, F. Vitillo, C. Garnier, X. Jeanningros, E. Rigal, F. Le Bourdais, S. Madeleine, O. Gastaldi, G. Laffont, Status of the Sodium Gas Heat Exchanger (SGHE) development for the Nitrogen Power Conversion System planned for the ASTRID SFR prototype, Proceedings of ICAPP 2015, May 03-06, 2015 - Nice (France), Paper 15362

[3] X. Li, R. Le Pierres, S. J. Dewson, Heat Exchangers for the Next Generation of Nuclear Reactors, Proceedings of ICAPP '06 Reno, NV USA, June 4-8, 2006, Paper 6105.

[4] P. Lorenzetto, W. Daenner, C. Boudot, P. Bucci, K. Ioki, S. Tahtinen, Manufacture of primary first wall panel prototypes for the ITER blanket shield modules, 20th symposium on fusion engineering, 14-17 oct 2003

[5] A. Cardella, E. Rigal, L. Bedel, Ph. Bucci, J. Fiek, L. Forest, L.V. Boccaccini, E. Diegele, L. Giancarli, S. Hermsmeyer, G. Janeschitz, R. Laesser, A. Li Puma, J.D. Lulewicz, A. Moeslang, Y. Poitevin, E. Rabaglino, The manufacturing technologies of the European breeding blankets, J. Nucl. Mat. 329–333 (2004) 133–140

[6] N. Bouquet, E. Rigal, S. Chomette, Influence of industrial sheet surface finish on interface formation during HIP-bonding of austenitic stainless steel, Int. Conf. HIP, Stockholm, Sweden, 2014

[7] M. Maunay, PhD thesis, university Grenoble Alpes, 2018 (in French)