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HIGHLY EFFICIENT PLATE-FIN HEAT EXCHANGER (PFHE) TECHNICAL DEVELOPMENT FOR S-CO_2 POWER CYCLES

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ABSTRACT

Among all the equipments required for advanced Brayton cycles using supercritical CO_2 (s-CO_2), heat exchangers are clearly key components. Fives Cryo, with its expertise in thermal-hydraulic design and brazing fabrication is developing a compact, and highly efficient heat exchangers for s-CO_2 power cycles, thanks to their heat exchange capability with low pinch and high available flow sections. The aim of the development of this specific heat exchanger technology is to achieve an elevated degree of regeneration with recuperators at low and high temperatures. Plate-Fin Heat Exchanger (PFHE) is then a seductive solution to meet the desired thermal duty with low pressure drop leading to a reduction in size and capital cost. The enhancement of the mechanical integrity of PFHE equipment would lead to compete with, and even outweigh, Printed Circuit Heat Exchangers (PCHE) technology.

s-CO_2 Cycle conditions expose heat exchangers to severe conditions up to 500 °C and 250 bar. Base material selection is essential, and for cost reasons, it is important to keep affordable heat-resistant austenitic stainless steel grades, much cheaper than a nickel-based alloy. Another advantage of high compactness of PFHE is the diminution of the amount of material used in the heat exchanger fabrication, decreasing even more its cost.
The challenge presented here is to qualify PFHE, especially its mechanical resistance, at cycle operating conditions. To reach the requirements, several fabrication fields were explored.

One critical point is the design of the fins. As secondary surface they permit the maximization of heat transfer at a low pressure drop. At the same time mechanical strength has to be guaranteed. To withstand high pressure, fins thickness has to be significant, which makes the implementation complicated. Efforts were dedicated to successfully obtain an optimal shape. Forming of fins was therefore improved compared to conventional techniques. Important work was undertaken to define industrial settings to flatten the top of the fins leading to a maximum contact between the brazing alloy and the fins. Consequently brazed joints quantity is minimized inducing a diminution of the presence of eutectic phase, which is structurally brittle and limits the mechanical strength of the construction.
A detailed metallurgical study brings other elements leading to the prevention of premature rupture of the brazed structure. The idea is to determine an optimized solidification path and to identify a temperature range and holding time where the brazed joint is almost free of eutectic phase during the assembly process in the vacuum furnace.

INTRODUCTION

The Brayton cycle is the working principle of gas turbine engines. It can be a closed or open cycle. For classical open Brayton cycles, the working fluid from the compressor is injected into a combustion chamber where the high pressure fluid is mixed with fuel. In this case, the fluid is generally air. Closed Brayton cycles replace the combustion chamber with two heat exchangers following the compressor and the turbine. The working fluid in this

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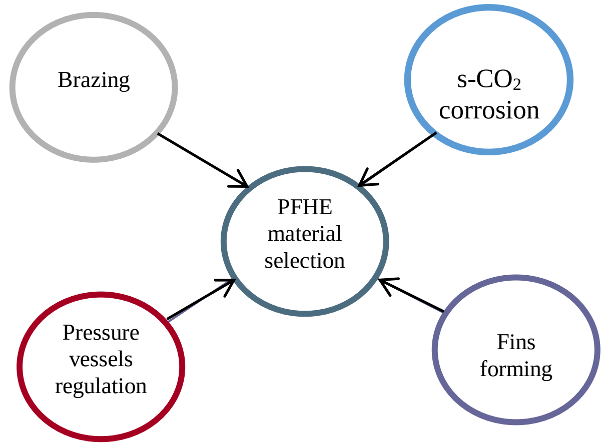
case is recycled continuously. The heat exchanger following the compressor, enhance the energy of the working fluid in order to activate the turbine, goes through the second heat exchanger which cool it to restore its initial conditions to go back into the compressor ([1], [2]). The working principle of the closed Brayton cycle shows the importance of heat exchangers in the thermodynamic process. These equipments need to be compact and able to be operated under severe mechanical and environmental constraints.

For Brayton cycles applications using supercritical CO_2, PCHE technology is mostly used thanks to its design capabilities: PCHE can be used for very high pressure and temperature conditions, compared to classical FPHE ([3], [4], [5]). Nevertheless, according to their important compactness and their economic interest, if the mechanical properties of FPHE and its integrity could be improved to reach PCHE performances, it would be the perfect choice in this field, since PCHE is a very expensive equipment, due to its important material density and the diffusion bonding assembly technique. Our work presented in this paper is achieved in the framework of this goal.

At Fives Cryo, we have a good knowledge in designing and manufacturing brazed PFHEs, which help us developing very efficient heat exchangers, in order to meet the requirements needed for s-CO_2 power cycles as part of the s-CO_2-flex European project. Recuperators are therefore developed, which should operate under pressures up to 250 bars and temperatures of about 500°C, in a s-CO_2 corrosive environment, due to its impurities content (water, oxygen …). PFHE can be made with quite large channels compared to PCHE, which permit to reach moderate pressure drop. The main objectives of the development are to propose a heat exchanger based on that technology that meets several requirements while increasing the cycle's efficiency. Quite a few aspects were investigated and among them to perform the design, the manufacturing, and to test it under the defined conditions.
The main tasks to consider are thus:

- to define appropriate materials for contact with high temperature impure s-CO_2 on the basis of corrosion tests,
- to achieve mechanical tests to satisfy operating conditions,
- to design and manufacture the heat exchanger by brazing and welding
- Finally, to confirm thermal and hydraulic performances of the heat exchanger.

The diagram below summarizes these tasks.



This paper mainly focuses on the work performed in the frame of manufacturing a plate-fin design that can withstand high-temperature and high temperature conditions and also survives in corrosion environment. The technical challenge is to determine a suitable configuration for all the constraints imposed by this process.

MATERIAL SELECTION

Depending on material interaction with CO_2 stream and available information on impurities content such as oxygen or water that affect corrosion rates, some candidate alloys cannot be employed. Brazing as an assembly technique has also to be evaluated on potential reaction rates with the circulating working fluid in the cycle. Little information is available, especially in supercritical conditions thus, corrosion data results are needed.
Furthermore, corrosion consideration has to be done in accordance with suitable mechanical strength. A selection of materials has to be discarded as they are not permitted to be employed at a level of 500 °C according to the boilers and pressure vessels regulation. Other concerns mainly deal with fins formability, and capacity of the alloy to be assembled by brazing and welding.

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Consequently, a shortlist of 3 different alloys was established: were selected, an austenitic stainless steel alloy compatible with brazing/welding conditions and aluminized in order to improve its corrosion resistance; a nickel-based alloy, which is certainly the more convenient choice for high corrosion resistance in drastic conditions and high mechanical resistance but presents the higher cost ; and a coated carbon steel alloy, which is a very innovative solution and could be very interesting economically and mechanically, but it needs to be validated for industrial use. The testing of these materials is still carried out by external contributors to the project, at s-CO_2 cycle's maximum temperature (500°C), hence, the results will not be included in the present paper.

This material selection clearly impacts the design of PFHE which is the result of a compromise but it should keep an advantage of high recuperation capacity at a moderate cost.

Despite the current lack of information on the corrosion resistance of the selected materials, we will relate in the sequel of this paper, the work achieved to enhance the mechanical resistance of PFHE assembly.

MECHANICAL RESISTANCE

An overview of basic elements necessary for the construction of a Plate-Fin Heat Exchanger can be seen on **Figure 1,** where the 3 flows are modeled by green, blue and red colors to illustrate the capability of this technology to withstand multiple flows. For s-CO_2 cycles, only 2 fluids are circulating for heat exchange.

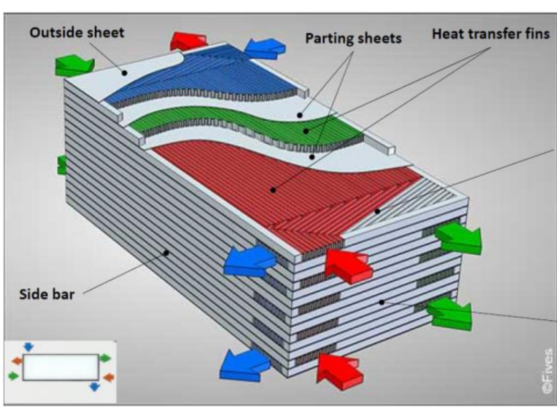

Figure 1: Example of a standard design of a Plate- Fin Heat Exchanger (PFHE) manufactured at Fives Cryo.

It consists of multiple layers of corrugated metal fins, separated by plates and closed with bars at the edges. The structure is joined together by brazing **(Figure 2)**. The fluids circulate in the different layers thanks to headers welded on the collecting areas.

In the light of the project, PFHE have to be qualified considering that this heat exchanger technology is not known as the best solution for s-CO_2 Brayton cycles due to the maximum temperature and pressure limitations. PCHE (Printed Circuit Heat Exchanger) is preferred regarding its structural characteristics ([3], [4], [5]): it is manufactured with a succession of printed plates. It can handle very high mechanical constraints at the cost of higher pressure drop and economical cost compared to PFHE. The differences between these two technologies are described in **Figure 2** below.

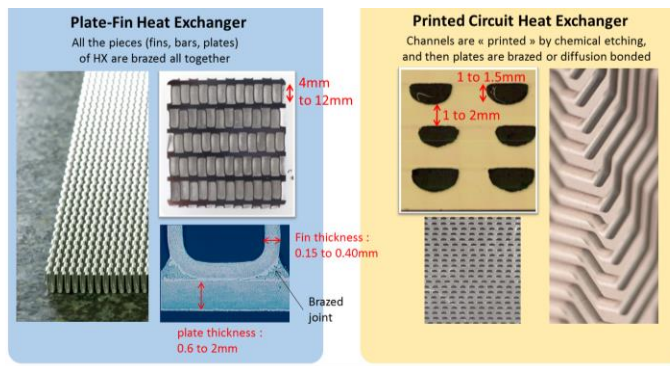

Figure 2: Comparison of two compact heat exchangers: PFHE versus PCHE

Forming process of the fins

In order to understand the mechanical design of a PFHE, it is important to clarify how Fives Cryo proceeds to form the fins:
We manufacture our own fin dies, according to defined fin geometry, and we install them on a hydraulic fin press machines. Fins are obtained by successive bending of flat sheets.

The continuous challenge is to control the deformation of the material to give the desired shape to the material.

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Brazing process

Fins parts are then cleaned in order to remove the grease of the stamping machines or any dirt that could affect the quality of the brazing procedure.

The parting sheets are recovered by a specific amount of Ni based brazing filler metal. The melting point of this filler metal is slightly lower than the stainless steel (the filler metal liquidus is below the solidus of the base metal), which will ensure the stiffness of the assembly when it solidifies.

The different elements constituting the heat exchanger (fins, bars, parting sheets and external plates) are then stacked according to detailed sketches.

After the stacking of all these elements, the assembly is compressed via a specific tool, in order to prevent any movement or displacement of the stacked elements which may compromise the integrity of the exchanger.

The brazing occurs in a vacuum furnace. A confidential specific cycle is applied, and the evolution of the temperature in the matrix is monitored via thermocouples. This step is very important to ensure a homogeneous heating of the assembly.

The manufacturing of such equipments is submitted to the requirements of pressure vessels codes, among them the ASME (American Standards of Mechanical Engineers) code.

Validation of mechanical strength is mandatory to authorize the equipment and to operate the heat exchanger at temperature and pressure imposed by the specifications. This is particularly recommended to perform bursting tests on representative brazed samples (see on **Figure 3**). As the assembly technique should not be the weak point of the structure, the rupture should occur in the fins which are formed from the base material selected.

The bursting tests allows to validate the ability of the fins to resist the actual applied pressure to the heat exchanger, applying a safety factor.

According to the regulation, we need to determine a Maximum Allowable Working Pressure (MAWP) via an approved method by the code.

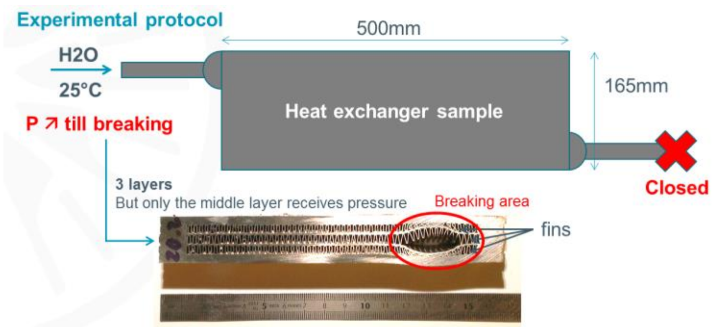

Figure 3: example of a burst brazed sample

The bursting test (**Figure 3**) consists of manufacturing a triple layer prototype of PFHE, which will be tested under pressurized water flowing in the middle layer (the top and bottom layers are dummys). The rupture should happen in the legs of the fins (base material). Otherwise, if it occurs in the brazed joint, the test fails.
The obtained bursting pressure is then converted to a MAWP via formulas given by the applicable pressure vessels code. This MAWP will determine the limit of the design pressure of the equipment at design temperature. A safety factor is then applied: for example, considering the ASME code, the MAWP strongly depends on the operating temperature. In fact, the bursting pressure is converted first into a maximum allowable working pressure at ambient temperature (which is the bursting test temperature), and then, to a maximum allowable working pressure at the operating temperature (which is equal to 500°C for our s-CO_2 cycle), according to the following formulas:

$$MAWP = P\frac{S}{S_2}$$

$$P = \frac{B}{4} \times \frac{S_\mu}{S_{\mu avg}}$$

Where P is the maximum allowable working pressure at the design temperature; S the maximum allowable stress value at the design temperature, but not exceed S_2, which is the maximum allowable stress value for the material used in the test at test temperature; B the bursting test pressure, S_μ the specified minimum tensile strength at

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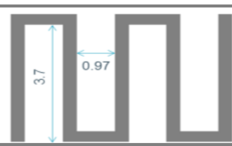
room temperature; and $S_{\mu avg}$ the average actual tensile strength of test specimens at room temperature.

One aim of the work undertaken here is to successfully design a PFHE matrix compatible with s-CO_2 Flex cycle conditions and competitive with PCHE.
Two types of heat exchangers are required for the cycle: a low temperature recuperator (LTR) and a high temperature recuperator (HTR). One stream is circulating in these heat exchangers at a high pressure close to 250 bars. The focus of the present study is the development of a HTR, which can be operated at s-CO_2 cycle conditions.
A dedicated fin with preliminary characteristics is proposed (see **Table 1** below for geometry description). The geometry was evaluated to conform to design conditions, as material mechanical strength is varying with temperature.

Table 1: Geometrical description of the fins

HT-HP Fin characteristics	
Thickness (mm)	0.3
Height (mm)	4
FPM (Fin Per meter)	787.4
Geometry	

A 316 stainless steel grade is used to manufacture brazed samples and fins in particular. This material has normalized mechanical characteristics.
According to the ASME code, a value of approximatively 1500 bar would be necessary to achieve at the bursting tests for qualifying this assembly for a use at 500°C at 250 bar.

First tests results indicated that a bursting pressure of 800 bar were reached. This value is low compared to the required one. Furthermore, the rupture occurred in the brazed joint (**Figure 4**) and not in the fins legs, this does not validate the test.

Intrinsically, this structure should resist at a higher level of mechanical stress. The analysis of the location of the rupture (**Figure 4**) revealed that the brazed zone is composed of a brittle phase and a ductile one. The ductile phase is located on the top of the fins only, which is not sufficient to preserve the mechanical properties of the entire brazed joint. The microstructure in this area has to contain as little fragile phase as possible, in order not to be mechanically limiting.

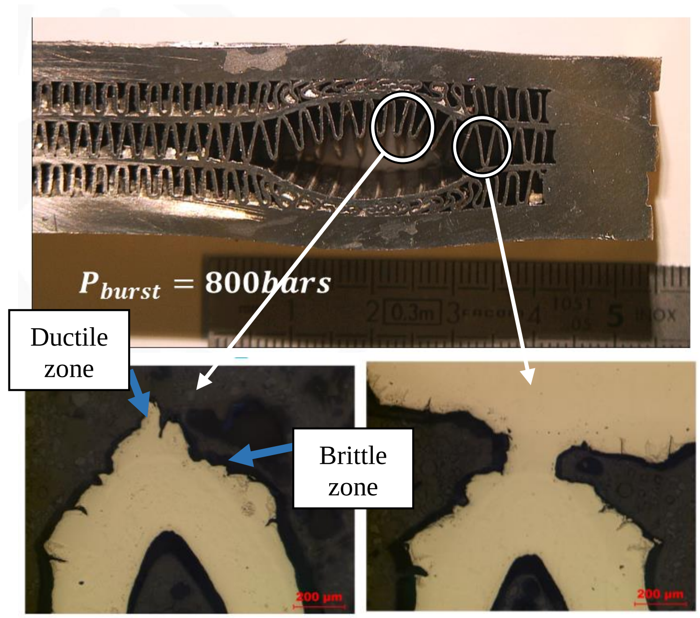


Figure 3: Fins rupture area, showing the presence of a ductile zone and a fragile brittle zone in the filler metal.

A metallurgical study was carried out to better understand what the root cause of this weakness is. It revealed that the origin of the premature rupture is the formation of a eutectic brittle phase (**Figure 5**), which influences highly the mechanical resistance of the assembly.

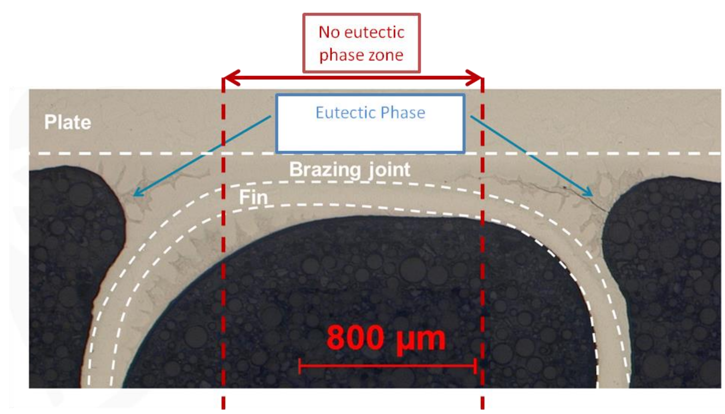


Figure 4: Micrograph images of the brazed region between fins and the plate, showing the presence of a eutectic phase on the edge of the brazed joint

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In order to reduce the area of the eutectic phase and increase the mechanical properties of the brazed joint, it is possible to consider the following options:

- To optimize the fins' geometry by forming a flat top and get a square overall shape and thus limiting the amount of brazing in this critical area (**Figure 6**),
- To improve the brazing cycle to lead to a homogenization of the microstructure.

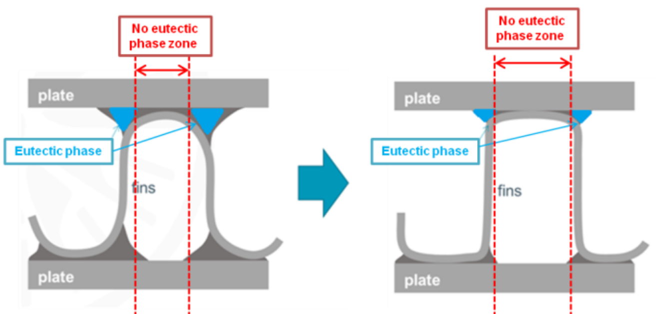


Figure 5: Schematic representation of the geometric enhancement of the fins with circular and square shape

Optimization of the fins geometry

Fins are obtained from flat sheets by successive bending thanks to fin stamping presses used in conjunction with fin dies. These tools are designed for deformation and this deformation application gives the desired shape to the material.
In order to reduce the amount of the brittle phase in the brazed joint, the geometry of our stamping machine tools was adapted, to flatten as much as possible the top of the fins (**Figure 7**). A proprietary system was developed to do so.

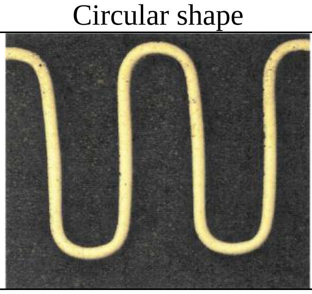
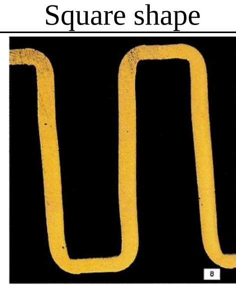
Circular shape	Square shape
	

Figure 6: Micrograph images of the fins before and after the shape modification

The bursting tests realized on brazed samples assembled with these new fins showed an important increase in the mechanical strength of the brazed structure. Indeed the bursting pressure reached was 1200 bars, and the rupture occurred in the base metal that time (**Figure 8).**
Analyzing intimately the rupture, it can be observed that it started at the fins radius. This area is clearly thinned by 15% compared to the initial thickness of the strip coil due to the forming process.
The challenge is to counter this thickness reduction, which will lead to a higher mechanical strength, by working on the shape of the stamping machine tool. Another way is to change the base metal with a material having higher mechanical properties. For the last option, it is mandatory to find a compromise between the material strength and its stamping ability to form suitable fins.

Figure 7: View of the rupture location of a brazed sample composed of "square"-shaped fins

Understanding of the solidification kinetics during the brazing cycle

A study is carried out focusing on transient liquid phase bonding (TLP) joining the austenitic stainless steel base metal using a nickel based brazing alloy.
The aim is to characterize the filler alloy and the joints bonded by TLP, in order to better understand the solidification path and improve the brazing cycle and assembly quality.
The process of TLP bonding consists on inserting a layer composed of a melting point depressant alloying element between the base metal layers. The melting of this interlayer at the brazing temperature results of joining the structure.

An isothermal holding time at this temperature permits the melting depressant element to diffuse into the base

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metal, which will modify the liquidus [6] and results in isothermal solidification (**Figure 9).**

For some cases, the isothermal solidification is incomplete: some of the liquid phase remains, solidifies while cooling, which leads to the formation of a eutectic brittle phases in the joints.

Long isothermal holding can prevent the appearance of these brittle phases, but has also a negative impact on the corrosion resistance of the base material due to sensitization by chromium depletion. In fact, in austenitic stainless steels, chromium carbide precipitates at grain boundaries: this phenomenon is called intergranular corrosion [7].

Long isothermal holding is also not economical from an industrial point of view and very time consuming.

All these points bring the high issues to determine the minimum time required to complete the isothermal solidification.

316 stainless steel specimens were prepared from 4 mm thick plate. The mating surfaces of the plates were mechanically ground to remove surface oxide layer, and the filler metal was applied. The plates were put in contact, and compressed with a stainless steel tool. TLP bonding was operated in a primary vacuum furnace at 1180°C, and then quenched in water. The thermal cycle details and the measurements techniques are explained in [8].

The phases formed in the filler metal after brazing, at the equilibrium were identified via measures of chemical compositions using EDX (energy dispersive X-ray spectrometry). The results details of these measurements will not be disclosed in this paper, due to some confidentiality issues. The identified phases are an austenitic solid solution and two silicides (which will be designated as phase A and phase B on **Figure 10**).

This permits to identify diffusion controlled aspects of the isothermal solidification. An investigation is in progress to determine an empirical formula. The aim is to estimate the necessary time for the completion of the isothermal solidification, based on the diffusion parameters. This will help to define a convenient brazing cycle leading to keep fair properties of the material regarding corrosion issues as explained before.

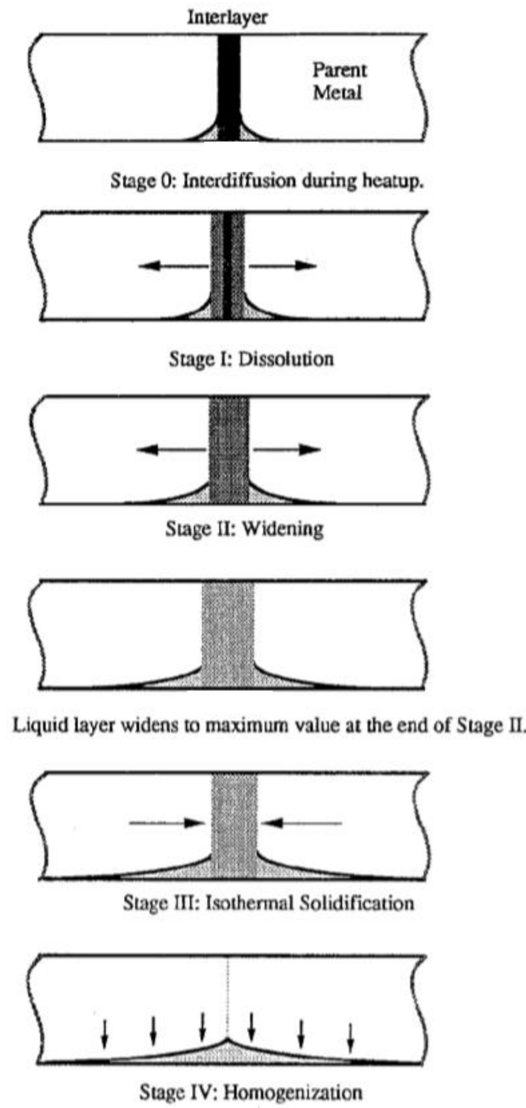

Figure 8: Stages of TLP bonding. The concentration of the melting point depressant is evidenced by the grey shading and the movement of the solid-liquid interface by the arrows [6]

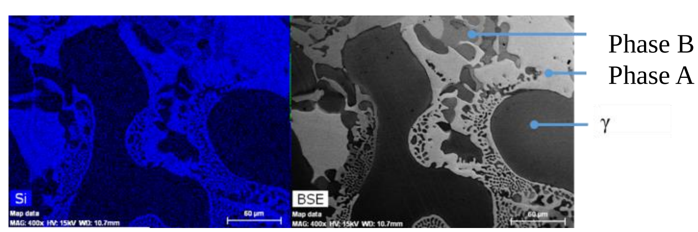

Figure 10: Si EDX and BSE (Back-scatter detector) maps of a solidified microstructure of the filler metal

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CONCLUSION

The s-CO_2 flex project aim is to develop and validate a Brayton cycle using supercritical CO_2 which will help to adapt fossil fuel power plants to integrate renewable energy sources.

Because of the nature of this working fluid, severe operating conditions are possible. In particular heat exchangers are confronted to a high level of temperature and pressure.

Usually, PCHE technology is the prior choice for this application thanks to its mechanical integrity and its thermal and hydraulic performances, but PFHE developed at Fives Cryo could be a better candidate for s-CO_2 Brayton cycle applications with its high degree of compactness at a moderate cost, if its mechanical and corrosion resistance are improved to bring internal structure at an opportune level.

To that end, a specific development is performed: in the frame of s-CO_2 flex project, Fives Cryo develops the manufacturing of both recuperators of the cycle (LTR & HTR), which are stainless steel heat exchangers, centering on following topics:

- selection of a material with high mechanical properties resistant to corrosion against impure supercritical CO_2 and validation by means of corrosion tests under real cycle conditions,
- extension of the mechanical strength of the PFHE structure to meet the process requirements, by developing new “square”-shaped fins. This modified geometry reduces the brittle phase presence in the brazed joint hence enhancing the solidity of the assembly,
- understanding of the solidification kinetics during the brazing cycle and determining of the most appropriate cycle parameters to get brazed joints as free as possible from brittle phases, while preserving the mechanical strength and the corrosion resistance of the base metal.

Currently, much progress has been made on the second and last topics. There is a fair confidence to succeed qualifying PFHE technology to be part of future s-CO_2 Brayton cycles in power plants.

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