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Archer
Advanced Reactor
for Cogeneration of
Heat & Electricity-R&D

Deliverable D-43.31:
IHX manufacturing report

Antoine PECHBERTY (ALP)
Frederic RONDET (ALV)

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Summary

Report on the whole manufacturing of the IHX mock up, presenting all work and steps perfomed, from machining to the insertion in pressure vessel, through welding and forming of plates.

Approval

Rev.	Short description	First author	WP Leader	SP leader	Coordinator
0	First issue	F.RONDET (ALV) A.PECHBERTY (ALP) 13/01/2015	D.LHACHEMI (AREVA)	D.BUCKTHORPE	S.KNOL (NRG) .../.../...

Distribution list

Name	Organisation	Comments
P. Manolatos	EC DG RTD	
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DELIVERABLE D-43.31
IHX MANUFACTURING REPORT

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Approbateur *Approver*	Pierre Xavier	BUSSONNET	Etudes Management (ALP)	13/01/2015

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SUMMARY

Introduction

In the framework of research on 4th generation nuclear reactors (Very High Temperature Reactors "VHTR"), the CEA, ALV and ALP developed an original concept of corrugated plate heat exchangers.
A feasibility study and the production of a prototype of an exchanger were carried out by ALV, ALP and the CEA. The study showed the full interest of the base concept.

All tasks done to develop and manuacture IHX mock-up are summarized in this document.

For its part, ALV developed the required welding and forming processes for the mock-up manufacturing, formed the plates by pressing and then welded them together after adjustment of the welding parameters, while ALP used his knowledge and its know-how about plate heat exchangers enclosed in a pressure vessel to develop the machining procedures and the integration of bundle in the pressure vessel.

ALV also provided representative welded samples for tests for Task 4.3.5.

Alfa Laval is a leading global provider of solutions to a large number of industries.
The core of Alfa Laval's operations is based on three key technologies for industrial companies:

- Heat transfer
- Separation
- Fluid handling

Alfa Laval VICARB (ALV) is the division of the group specialized in the development and production of all welded heat exchangers (excepted the PACKINOX), essentially dedicated for industrial processes.
The core of the heat exchangers is manufactured from metal sheets that are press formed (corrugated) and laser or GTAW welded together.
ALV has leading edge technology at its disposal, protected in part by patents and secret know-how, including the laser welding of thin press formed heat transfer plates.
ALV has developed also special partnership with several suppliers for the laser welding of such thin plates.

Alfa Laval PACKINOX (ALP) is the division of the group which develops and produces large welded plate heat exchangers for high temperature services, dedicated for oil and petrochemical industries, especially for feed/effluent applications. Heat exchangers are manufactured from metal sheets which are explosion formed underwater, then GTAW welded together.

ALV is working together with the AL headquarter located in Lund, Sweden, where, to master the entire chain, from design to production, Alfa Laval has set up a laboratory for thermo-hydraulic testing and mechanical testing with numerical simulation, as well as tools specific to its business, including press of very high capacity to press form the corrugated plates.
Those resources were of great benefits for the IHX project for the design and the manufacturing of the corrugated heat transfer plates of the heat exchanger core.

1. Objectives

The work package WP4.3 aims to demonstrate the feasibility of one real size IHX module by designing and manufacturing of one 'full size' mock-up made of Alloy 800H and by testingt it in the CEA's CLAIRE loop at operating conditions (750°C – 800°C) to assess the compact IHX (PSHE) lifetime. To reach this objective, CFD and FEM calculations was required in support, as well as set of tests on Alloy 800H thin sheets for behavior laws and creep tests on weld joints samples to estimate corresponding coefficients.

After supplying material (Alloy 800H) and providing samples for material tests, and after manufacturing of the shell and machining of the plates (ALP), forming (ALV) and welding (ALV), the assembling of the mock-up could be done (ALP). The IHX mock-up was delivered for the tests during autumn 2013 (M4332) and the final corresponding manufacturing report (D4331) released right after. This report excludes the processes and know-how that are proprietary and secret information of Alfa-Laval (ALP and ALV).

2. Manufacturing steps

Main manufacturing steps are summarized below, and are the following :
- machining of plates
- welding of plates
- manufacturing of pressure vessel and insertion of the bundle

Use of machining has been selected instead of raw plates in order to obtain the specific design of the "weldable edges", which are required to be monoblocks instead of made by welded sheets.

2.1. Machining

Machining of such material was difficult due to the low thermal conductivity and the amount of alloying element making the material abrasive for tools.
The second difficulty came from the plate itself, since such geometry requires a very specific clamping during machining, in order to avoid deformation and to comply with tight tolerances required by laser welding.

To obtain satisfactory final plates, several steps have been followed.

The first one was to perform machining of preliminary samples for welding tests. These tests aimed to test welding and machining of two types of edges for IHX plates, in order to select the most favorable design for welding and machining. The size of these samples was not representative of final plates, but to limit costs, only the edges needed to be as final plates.
These samples was made from the first batch of steel provided by ALP, assuming the thin part of plate centered and decentered in the thickness :

These small samples (250mm x 20mm) have been machined with mechanical clamping and several machining times. They brought out the difficulties to machine thin plates and to limit the deformations.
Results was good, but it was not usable for large plates, due to marks induced by machining times, incompatible with forming tools to not create any crack initiation during forming.

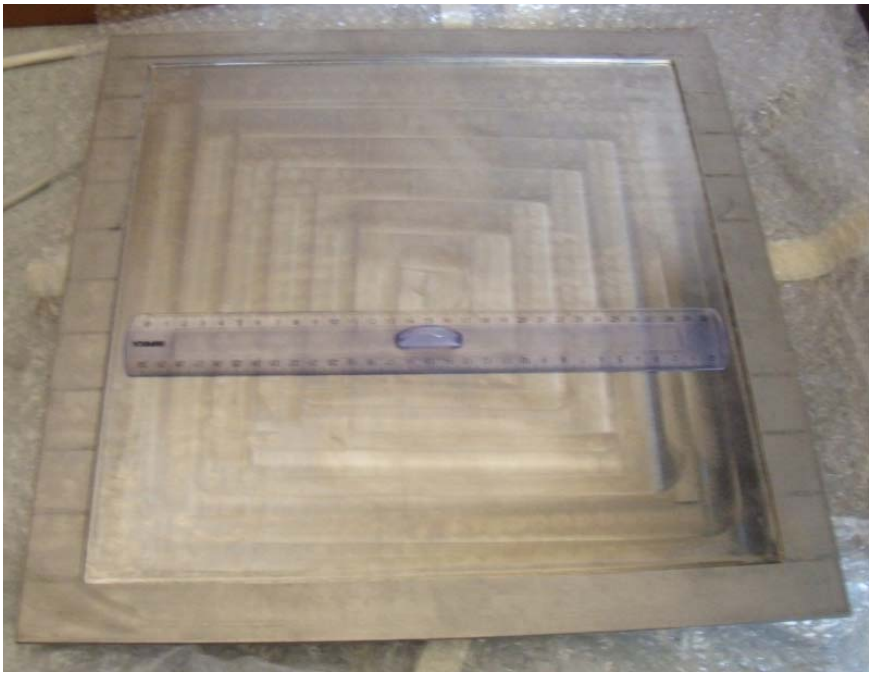
Welding an dmachining samples

Centered design

Decentered design

After selection of “centered design” for plates, and design of forming tools by AL lund, qualification of forming tools required to machine plates with intermediate size (393mm x 393mm), identical to final plates in term of width, thicknesses and edges.
Due to difficulties met on previous samples, these forming samples have been made with vacuum table, in order to ensure a perfect clamping, allowing to reduce machining tool marks and thickness variations. This process was the one identified, able to answer to the forming and welding requirements, since it allows to maintain the plate on all its area, especially in center, where there is no rigidity.

Regarding expected forming difficulties, these tests were used to try different surface roughnesses, the aim being to reduce as much as possible the time of machining while correct forming is ensured without any cracks. For some samples, a mechanical polishing has been added to machining procedure, in order to compare forming results with and without smooth surface roughness.



Machining and forming test samples

After these two campaigns of tests, complete machining process has been defined and applied as follow. For this, it was necessary to develop a custom vacuum table with mechanical clamps.

Custom vaccum table

Clamping of plate on vacuum table

Steps before forming

- A pouch (4mm to 1.5mm) is machined in the raw plate. The dimensions of the pouch are smaller than the required in order to keep material for additionnal passes.
Only one side of the plate is machined, in order to reduce the time for mounting/demounting and the time for machining.

- The four holes are machined with reduced diameter)
- The both faces of plates (inside of pouch and back face of plate) intended to be pressed are polished

The aim of these steps is to obtain a pouch ready to be formed, with the possibility to finish its shape by machining (length and width of plate, width of edge) after forming, in order to reduce as much as possible by machining the consequences of the deformations caused by forming

Machining of pouch

End of plate after 1st machining step, before forming

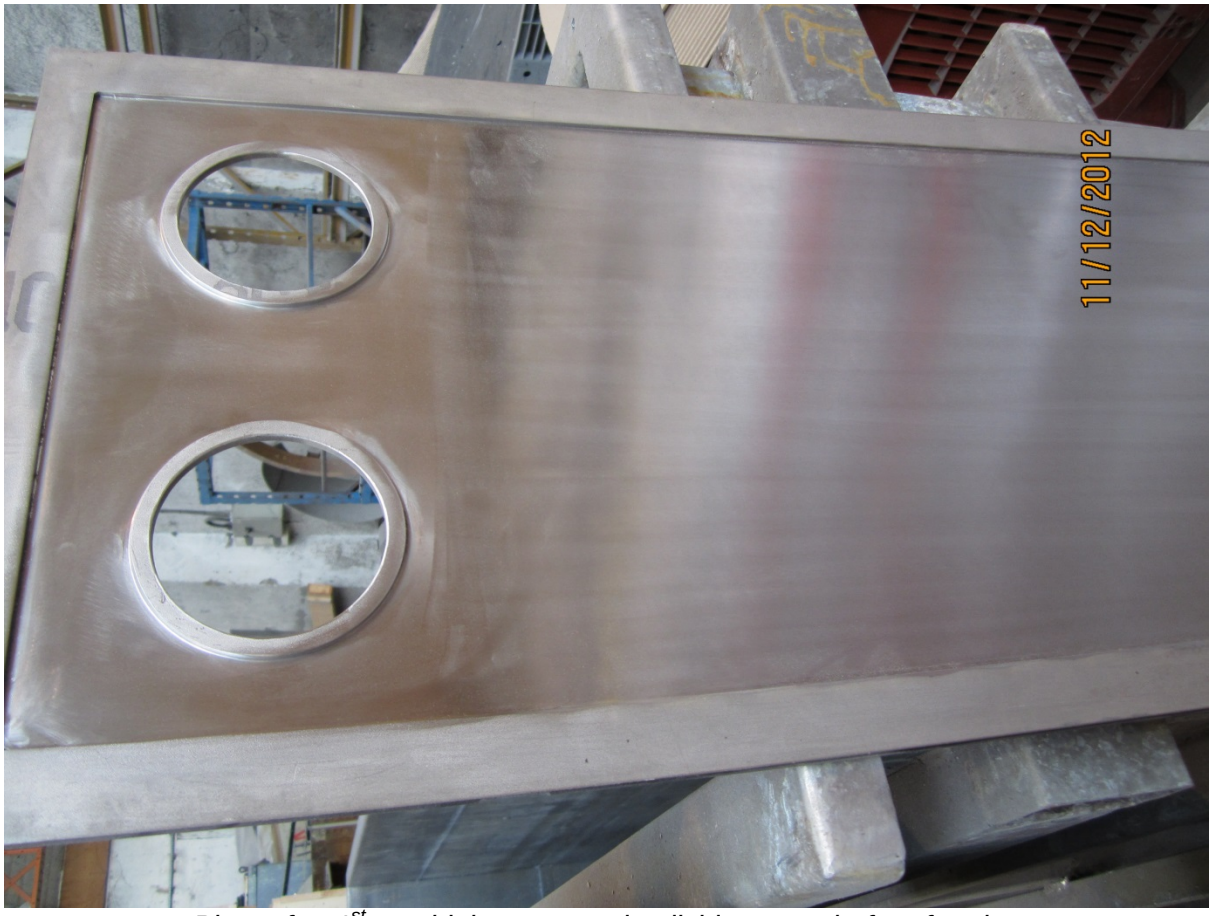
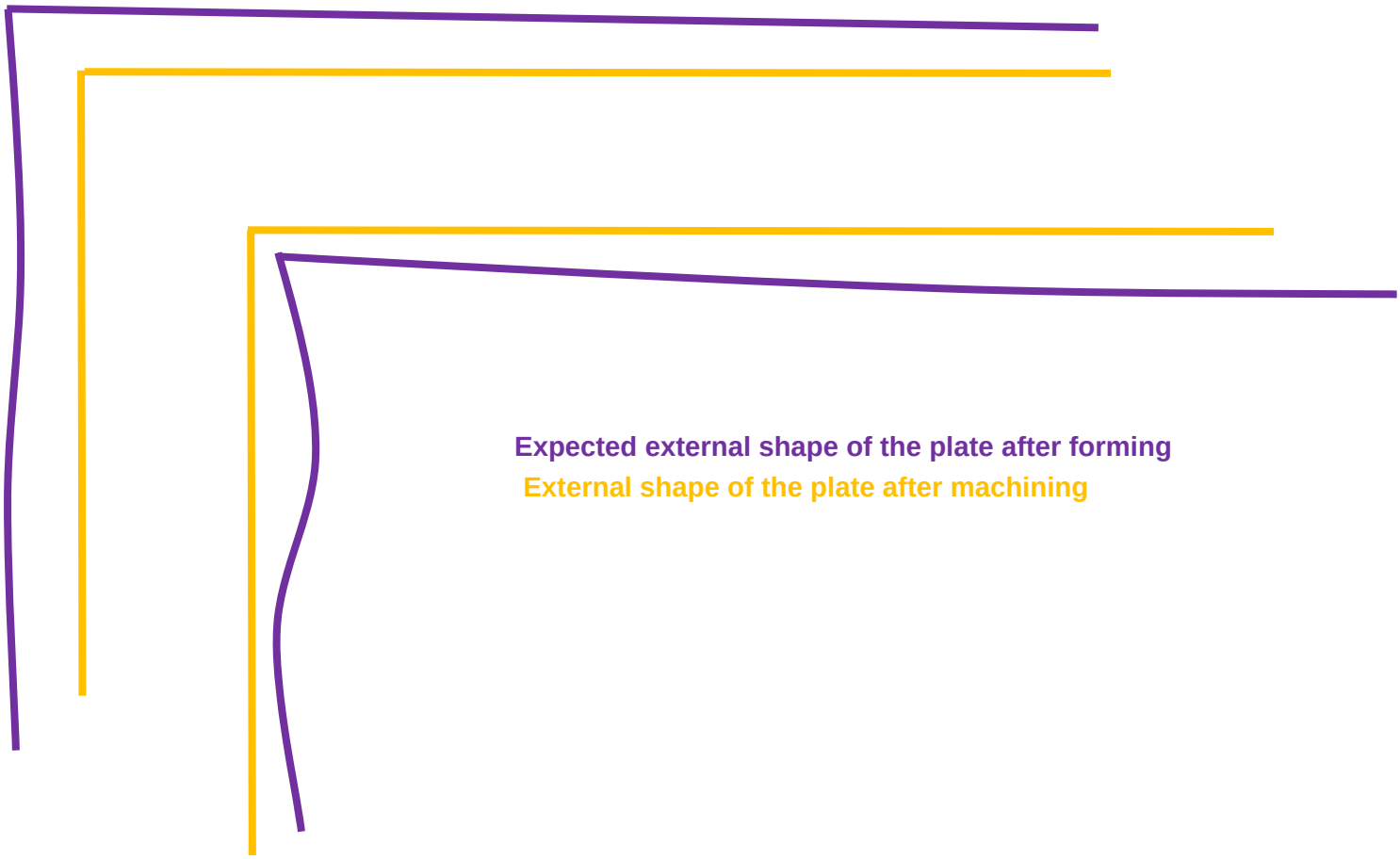


Plate after 1st machining step and polishing step, before forming

Steps after forming

- The four holes are machined again to give them their final dimension
- The external surface of plate is machined to give its final thickness (4mm to 3mm)
- The plate extra length and width is cutted by water jet. Machining is then performed to give the final dimensions of the plate and the final width of the edge (3mm)

Water jet cutting preliminary to machining has been selected in order to limit the time of machining. Indeed extra length and width was important (about 50mm) and involved to spend time to remove them. Water jet allowed to remove quickly an important amount of material, and machining has been used only to finish dimensions and get the right tolerances.
Even if these extra lengths are wasted, it could be not a good idea to reduce them, since they was very usefull, because they gave maximum stiffness to the plate during maching; they also allowed a mechanical clamping on the periphery of plates on the vacuum table, and they gave some margin on the width of the edge. Indeed, it was difficult to predict how the deformation after forming will be important, straightness of the edge being very important for laser beam welding.



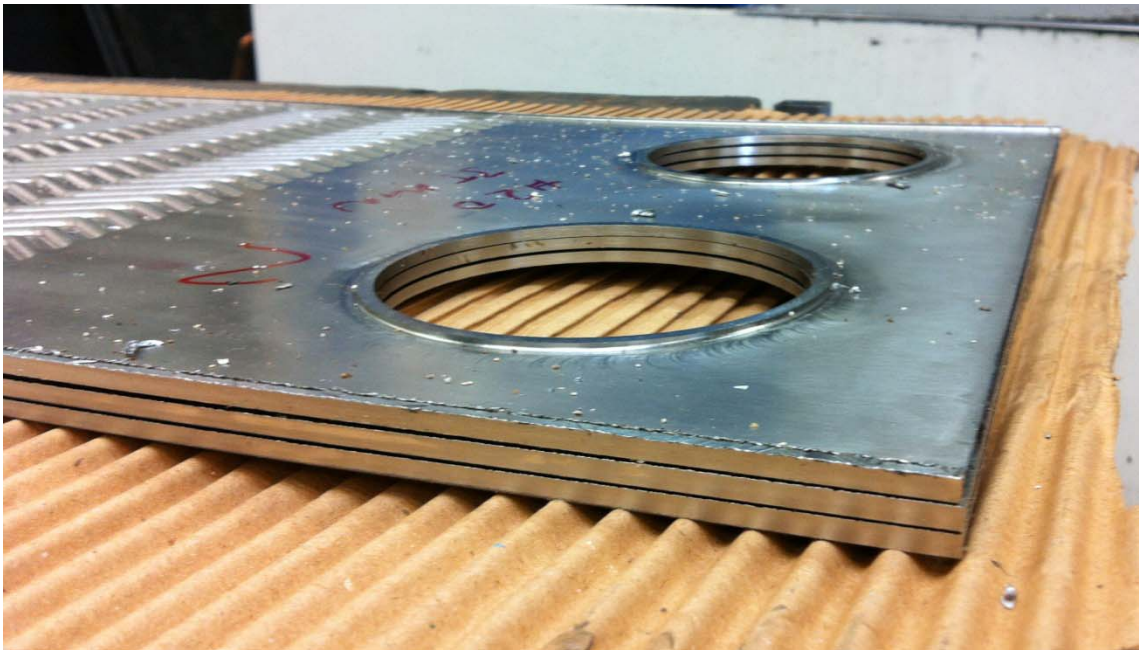


Plate just after maching

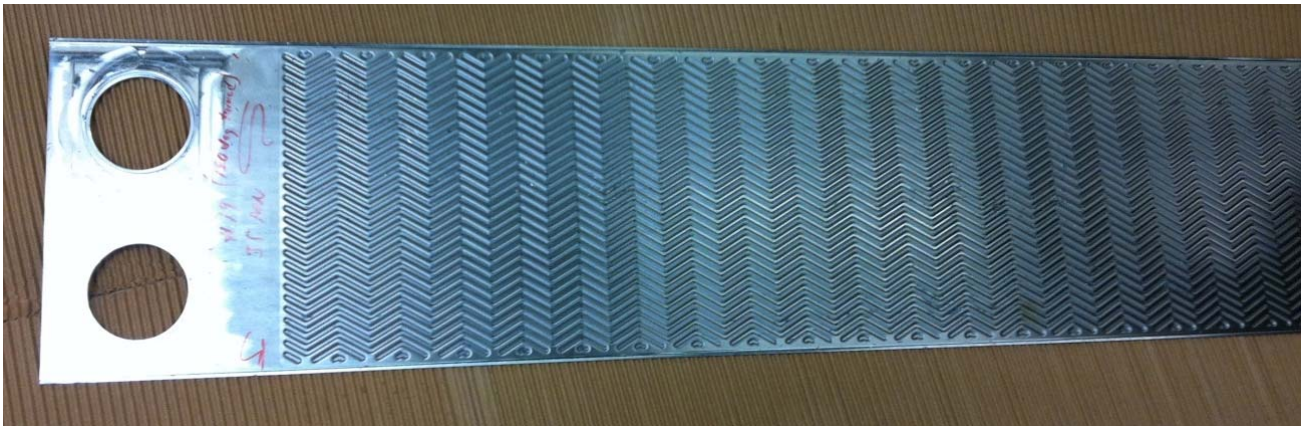


Plate after maching and forming

2.2. Machining - other ways

Few processes other than mechanical machining have been studied to produce these plates.

Chemical machining

Chemical machining has been considered to obtain the pouch and reduce the amount of chips. Chemical machining is often used in aviation indutry, to thin aluminium plates in order to reduce the weight of equipments, where thickness and strength are not necessary. But concerning our application, due to the very important thickness to remove (2.5mm), there a

risk a risk to degrade by very important way the roughness of plates. Indeed, chemical cleaning could amplify defects already present on plate.
Moreover, thicker is the thickness to remove, lesser is the accuracy of dimensions.

These two points being not in compliance with what it was required for forming and welding, such process has not been selected.
More generally, chemical attack on corrosion resitant alloy such as incoloy800H is difficult to control, and made this machining difficult.

Wire cutting
An other way to improve time of machining could be the use of wire cutting, which is an electro erosion process. This process allows to remove an imporant amount or material, with limited time, since the plates can be cutted together while stacked. The cut is also very accurate, great advantage for the final assembly and the welding.
But this process generates some oxydes on the area, which are not good for the welding. It has been tried to remove them by pickling, wihout succes. Consequently, it has been decided to abandon this process and to replace this step by classic machining

2.3. FORMING

The final objective of this sub-task is to deliver the heat transfer plates and the separate inserts (2 types) for the prototype with press formed heat transfer area.

Here are the main tasks to reach the goal:

- Based on earlier development made together with the CEA, propose a design of the heat transfer area that can be pressed with incoloy material and that can meet both the mechnical and thermal needs.

- Validate the geometry of the critical region especially the by-pass region, between the heat transfer region and the border of the plate

- Validate the raw sheet surface roughness needs for a good formability

- Validate the machined surface roughness needs for a good formability

- Validate the forming tools process with machined plates

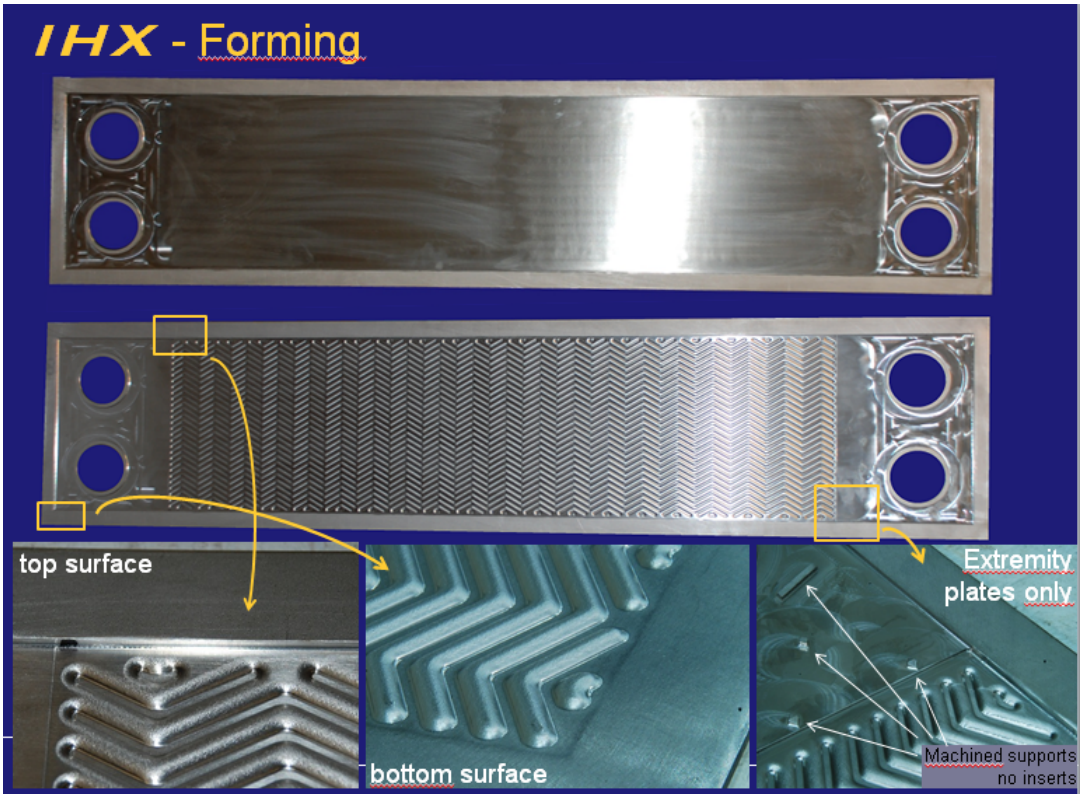
- Define the CAD geometry of the inserts based on the optimum current lines supplied by CEA CFD simulations

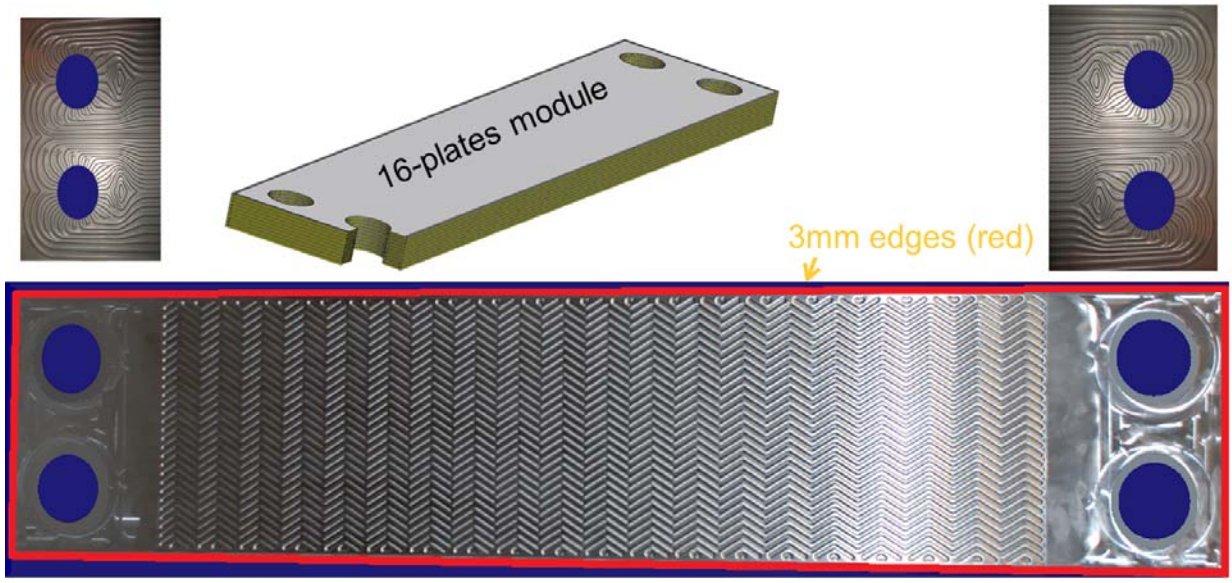
Here is the rough action plan that was followed:

- Design a small forming tool by CAD and do forming simulation to validate the profil and define a theoritical minimum for the by-pass gap

- Design the forming tools

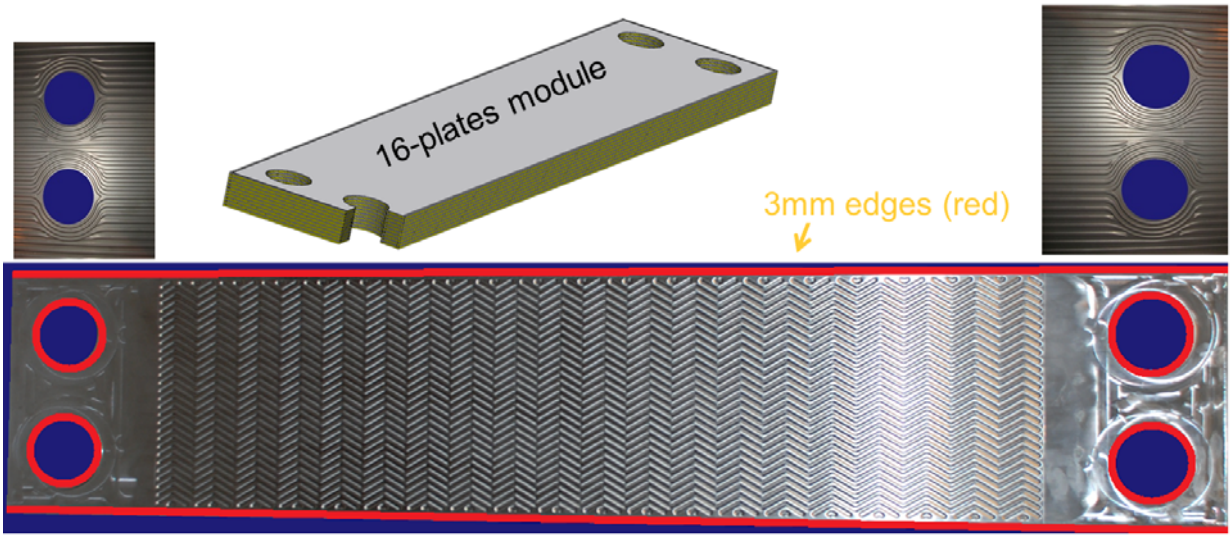
- Manufacture the pressing and forming tools
- Get from ALP some machined plates with different surface roughnesses on the raw side
- Get from ALP some machined plates with different surface roughnesses on the machined side
- Do some forming tests on small representative plates: machined and press formed
- Design the 3D of the forming tools and pressing tools for both the heat transfer plates and the inserts
- Supply the tools material
- Machine the forming tools and pressing tools for both the heat transfer plates and the inserts
- Press the heat transfer plates and the inserts
- Design the cutting fixture for the cutting of prototype inserts
- Cutting and washing of the heat transfer plates and the inserts





Heat Transfer plates type 1 with flat area in the distribution and the corresponding inserts

Heat Transfer plates type 1 with the inserts in place



Heat Transfer plates type 2 with flat area in the distribution and the corresponding inserts

Heat Transfer plates type 2 with the inserts in place

The main heat transfer region is identical on all the plates and the same forming tool was used for pressing those regions.
Some separate thin plate inserts were placed in the flat distribution regions (and spot laser welded) to optimize the thermal distribution and the pressure drop.

The design of those inserts is following at best the natural flow, which has been determined on the basis of CEA studies (see deliverable D43.11). The aim was to limit as much as possible the pressure drop generated by insert. For that, corrugations position was determined in order to follow the flow path obtained by CFD.
In some regions it was a little bit modified to optimize and to even the thermal gradients and reduce the peaks of stresses due to big temperature differences.

Forming after machining has never been done before, so some tests were needed in order to evaluate the impact of different parameters like the surface roughness and the deformation of the lateral plate walls.
A small rectangular tool representative of the main one was built and some pressing tests were done in order to check the impact of the surface roughness and to check the deformation level after pressing in the critical regions.

The plate walls needed to be slighlty remachined after forming in order to get a proper geometry for proper laser welding (0.1mm offset max accepted) and guaranty a full penetration or/and no defect from excessive welding pool.

A small gap between the formed area and the lateral walls was kept to help for forming and avoid brutal transition were cracks could have taken place during forming.

2.4. WELDING

The final objective of this sub-task is to deliver first some laser welded samples to Alstom for mechanical tests on the welded regions and then to laser weld the platepack built with the machined and press formed heat transfer plates assemblied with the separate inserts and thick extremity plates.

Here are the main tasks to reach the goal:

- Do some laser welding tests with flat plates in incoloy 800H in order to find the right parameters, in order to get a full penetration and without defects like liquations, pores, etc

- Using those parameters as a first reference, do some welding tests with machined plates, one side and two sides

- Based on laser weld test results select the optimum geometry for machined plates (one side or both sides machined)

- Refine the laser welding parameters with the selected geometry

- Search for all laser welding parameters for all combinations of geometries (1.5mm with 3mm, flat, circular, 3mm with 3mm, flat, 3mm with 8mm, flat, etc)

- Develop a totally new laser welding tool capable of welding in Ø80mm ports

- Weld 3 blocks using small representative samples with 7 welds so that Alstom can do some machining and get dog bone samples for mechanical tests.

Here is the rough action plan that was followed:

- Laser welding tests on flat plates of incoloy 800H in 3mm using several paramaters that can give a full penetration on straight lines, using a standard laser welding head

- Cross sections in order to check the presence of liquations

- Repeat the test with real samples representatives of the different combinations of thicknesses, do some cross sections and do some X-ray in order to check the presence of pores

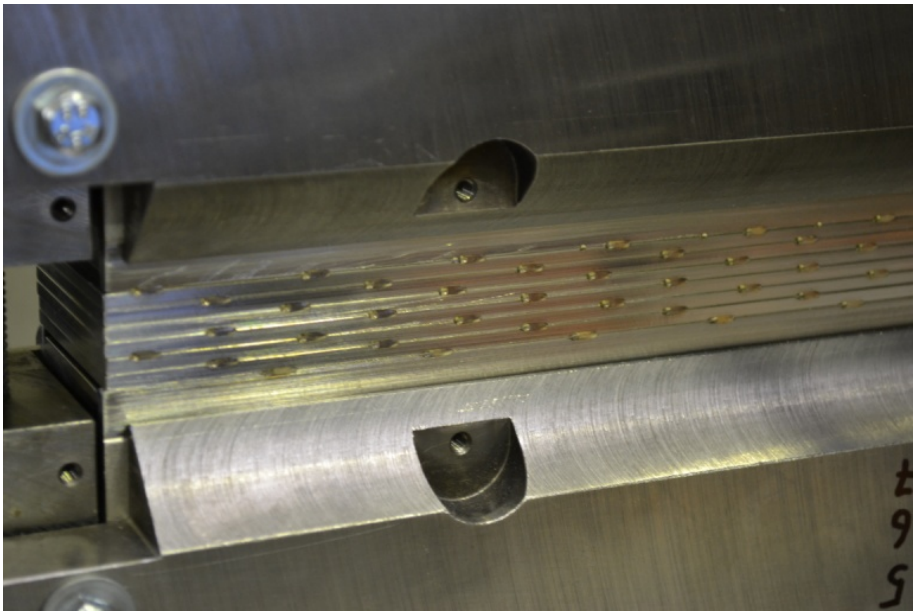
- Contact a laser integrator and design together a totally new laser welding tool capable of laser welding in Ø85mm ports with suficient level of energy for melting 3mm with 1.5mm incoloy 800H pates.

- Find the welding parameters and design a new gas protection system capable of producing laser welds free of liquations and other defects, yet with the full penetration.

- Design a new gas protection system for the weling of the outer edges of the plates

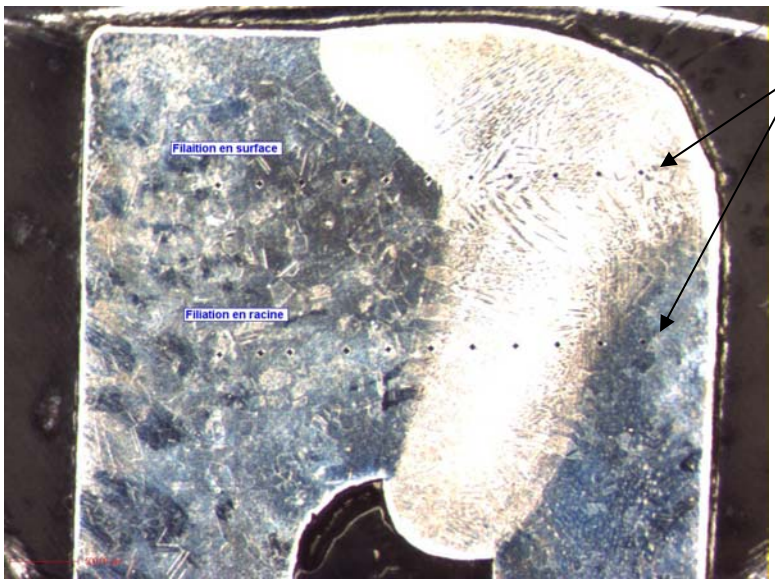
- Define a laser welding sequence that can minimize the deformations during welding

- Design the welding fixture for the Alstom welding samples



welding fixture for the Alstom welding samples

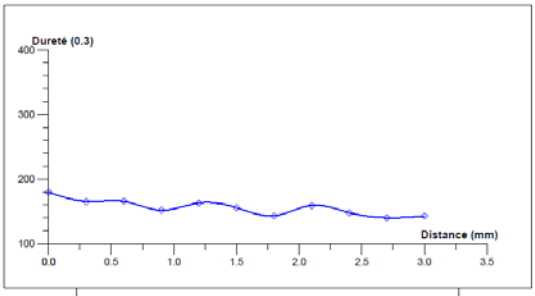
- Design the welding fixture for the welding of port welding samples
- Design the welding fixture for the welding of prototype ports
- Design the welding fixture for the welding of complete prototype (short and long edges)
- Design the welding fixture for the welding of prototype ports (Ø81mm)
- Do some measures of hardness in the vicinity of the joints in order to check the variation of hardness and that the 200Hv limit is not reached. We measured 160Hv peaks.



Checking close to the surface and deeper, closer to the weld root.

Bon de travail : IHX **Nuance** : Incoloy 800H-3mm
Référence : Soudure éprouvettes ALSTOM **Traitement** :
Opérateur : Cyril Roudeix **Signature** :

R & D

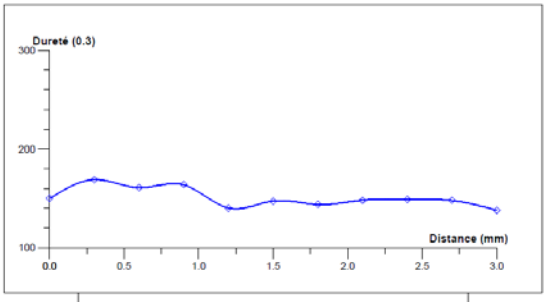


R & D

Mesure	Distance (mm)	Dureté 0.3
1	0	180
2	0.3	165
3	0.6	166
4	0.9	152
5	1.2	163
6	1.5	156
7	1.8	143
8	2.1	159
9	2.4	148
10	2.7	140
11	3	143

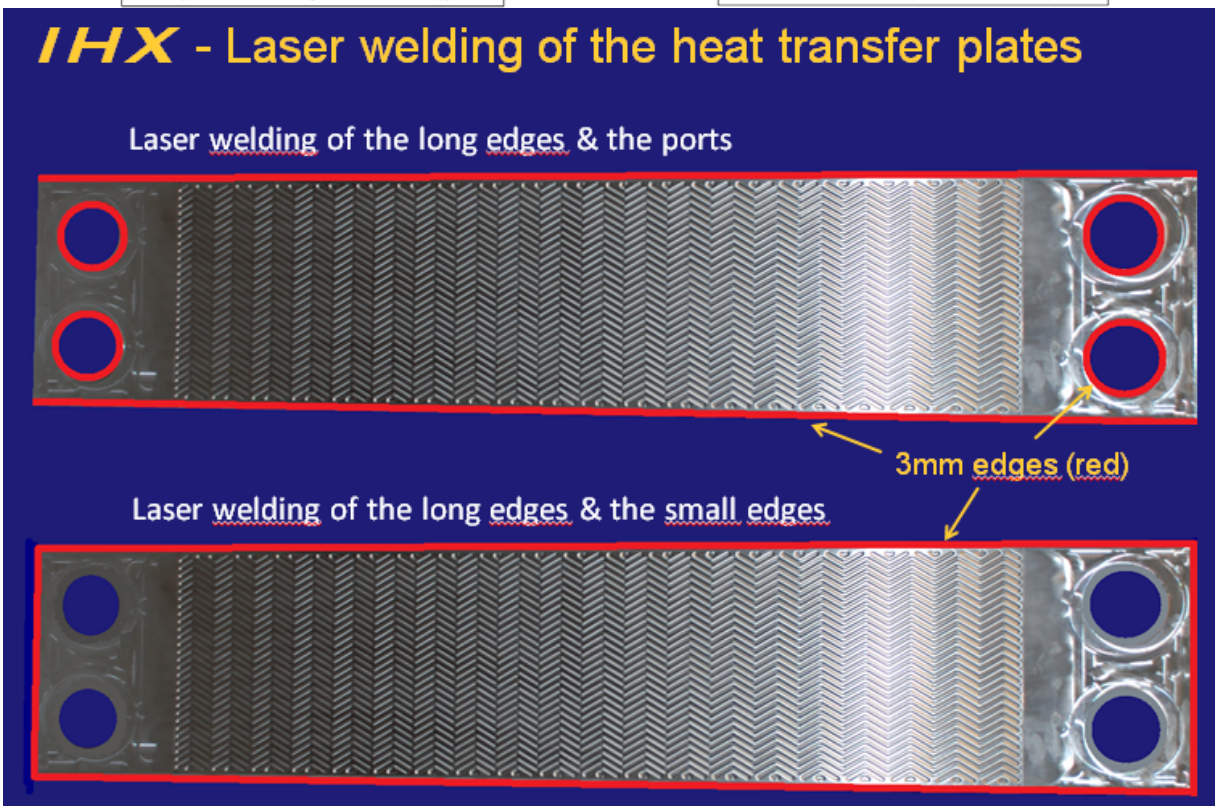
Bon de travail : IHX **Nuance** : Incoloy 800H-3mm
Référence : Soudure éprouvettes ALSTOM-Surface **Traitement** :
Opérateur : Cyril Roudeix **Signature** :

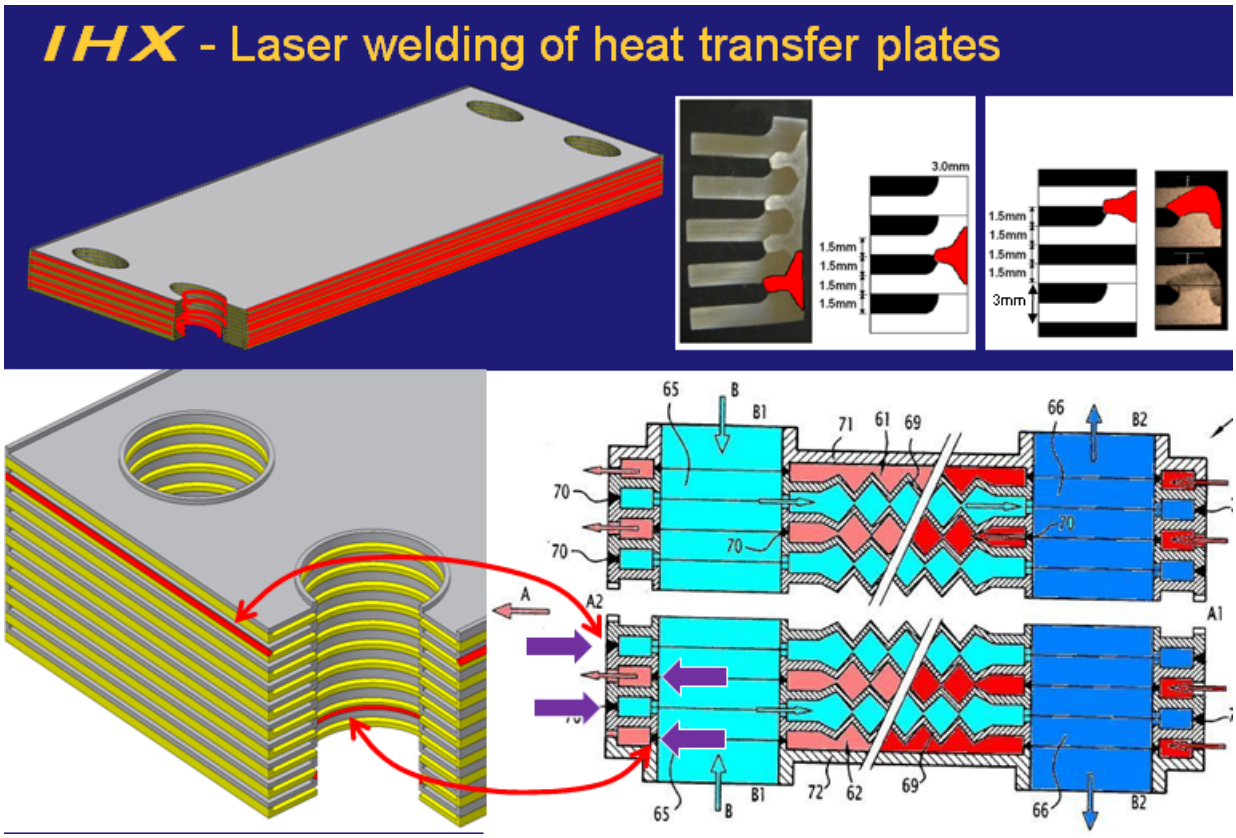
R & D

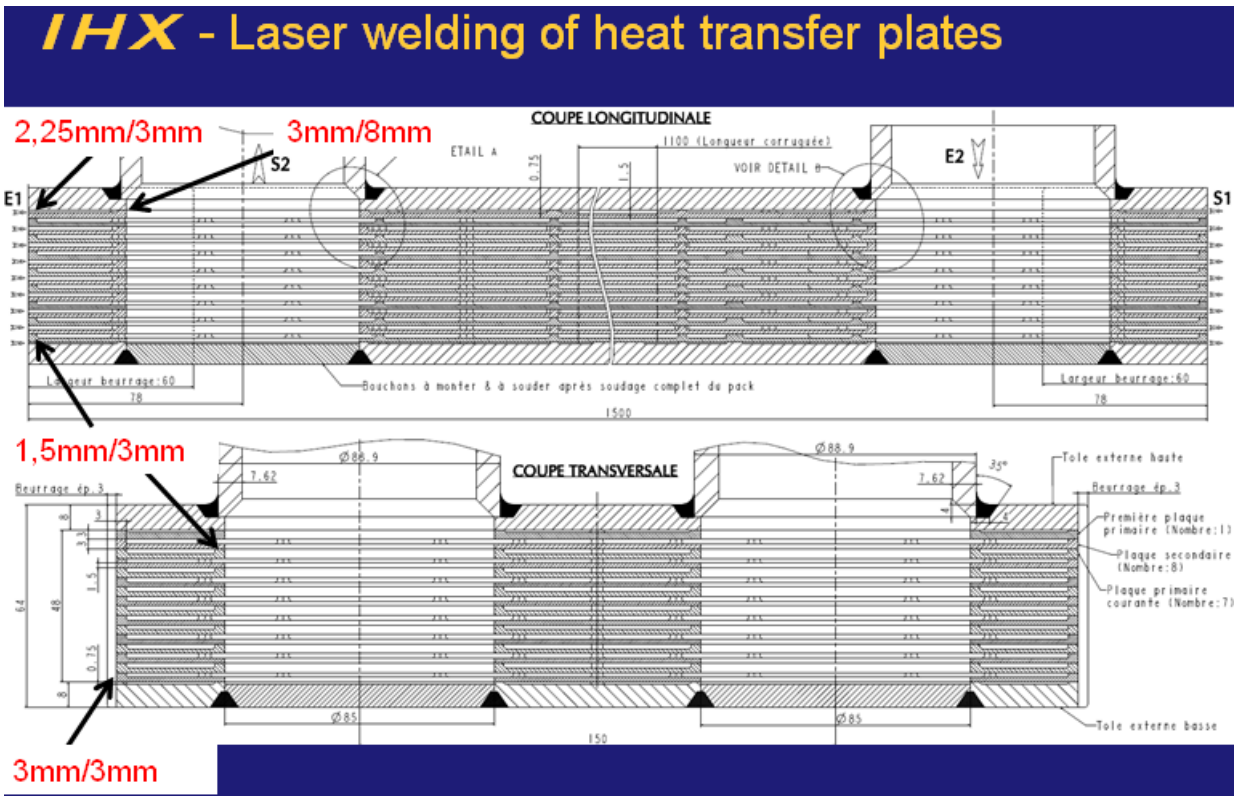


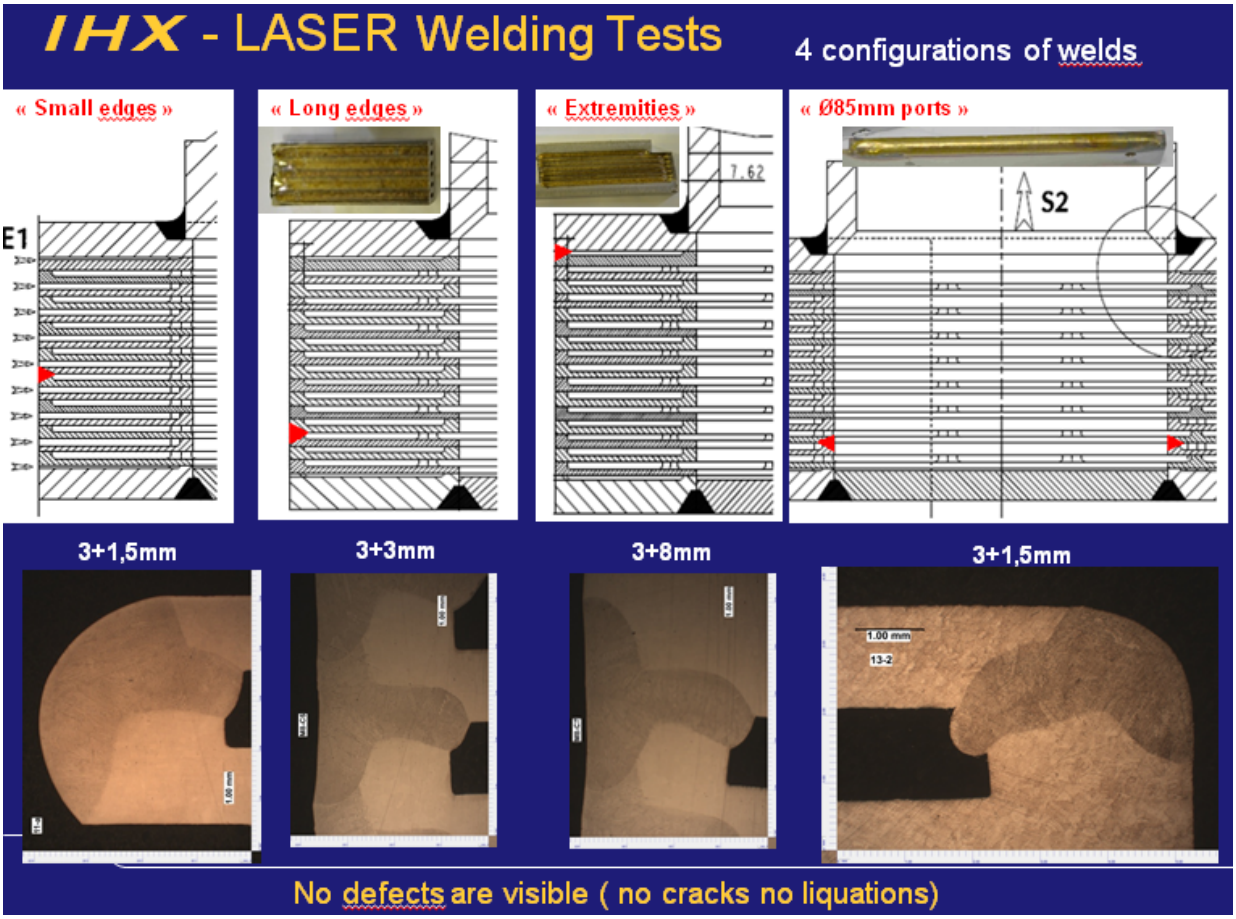
R & D

Mesure	Distance (mm)	Dureté 0.3
1	0	150
2	0.3	169
3	0.6	161
4	0.9	164
5	1.2	140
6	1.5	147
7	1.8	144
8	2.1	148
9	2.4	149
10	2.7	148
11	3	138









Thanks to the tests of the different geometries that are present in the prototype above, some final welding parameters could be found. The main difficulty with the alloy 800H was to find some welding conditions and parameters that could be repeated and automatically done to produce the welds without defect (hot cracking especially).
The liquation are some cracks that appear in the heat affected area if special cares are not taken.
A precise balance shall be found between power, speed, laser spot size, laser fiber size, gas protection (geometry, flowrate, etc) in order to succeed in this task. The welding was done at Université de Bourgogne, PLCB, using their robot and the laser head that we specially developped with Laser Machine for welding the Ø81mm ports.
We designed some fixtures in order to weld the cassettes first and then we stacked them in another fixture to achieve the outer welds and complete the platepack.
Before this step the cassettes welds were always tested by Helium test, just like the complete platepack at the very end of its welding

As the two welding tools have different geometries, different welding parameters had to found.

The laser welding head for welding the ports had to developed completely, including the gas protection. Many tests had to been done regularly to validate the new concepts and progress step by step.

The design is made such that the height of the platepack can be changed if necessary for a bigger platepack.
The choice of having the laser head controlled by linear motors instead of using the robot was made to get a better accuracy of the spot positionning while welding.

For the welding of the prototype bundle, we started by welding the ports, using backside gas protection, then we welded the outer edges on the stacked cassettes to build the platepack.
Before wedling, the cassettes were tested by helium test.
The welding sequence was made to try balancing the deformations due to welding and heat input in the parts.

2.5. INSERTION IN A PRESSURE VESSEL

To operate the IHX mock up bundle, it was necessary to enclose it in a pressure vessel. The design selected for the mock up is not the design selected for the future IHX application, but partners decided to focus on the bundle and its tests, in order to remove as much as possible the variables wich could disturb the tests and add some doubts or incertitudes on the performances of the bundle. The integration of the bundle in a pressure vessel was one of this point, and it is why ALP's design has been retained. Consequently, the pressure vessel and connections with bundle were designed with care to minimize heat loss and pressure drop.
Moreover, this design, simpler and less expensive than the future IHX, allowed to concentrate all the efforts on the bundle.

The ALP's heat exchanger design consists to fill the pressure vessel with the highest pressure fluid before to feed the bundle. By this way, bundle is always compress by this fluid, while rest of bundle is at a lowest pressure due to pressure drop inside bundle, and has only to whistand to external pressure.

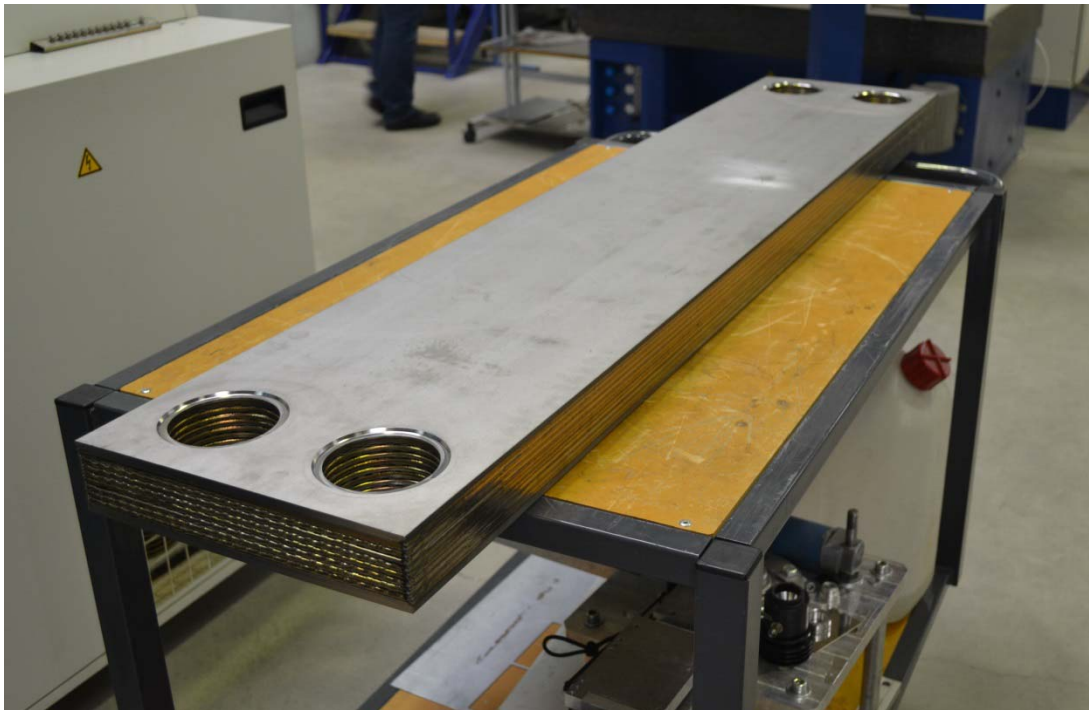
To reduce costs, the pressure vessel has been manufactured with both material Incoloy 800H and stainless steel 321, incoloy 800H being selected for the hot half part of equipment, and SS321 for the half cold part.

Pressure vessel has been designed according to the american pressure vessel code ASME, in addition to the european directive for pressure equipment PED since equipement is operated in France, in the CEA's facilities.

Inside the pressure vessel, the bundle is at the same time connected to the vessel and sustained by the cold fluid outlet. This avoid to have any concerns coming from differenrt thermal expansions between pressure vessel and bundle.
The hot inlet nozzle of bundle is made with concentric sleeves, in order to feed directly the bundle, while allowing to pressurize the pressure vessel. This design has been used to avoid the use of a bellow, impossible to design at this high temperature (design temperature : 815°C)

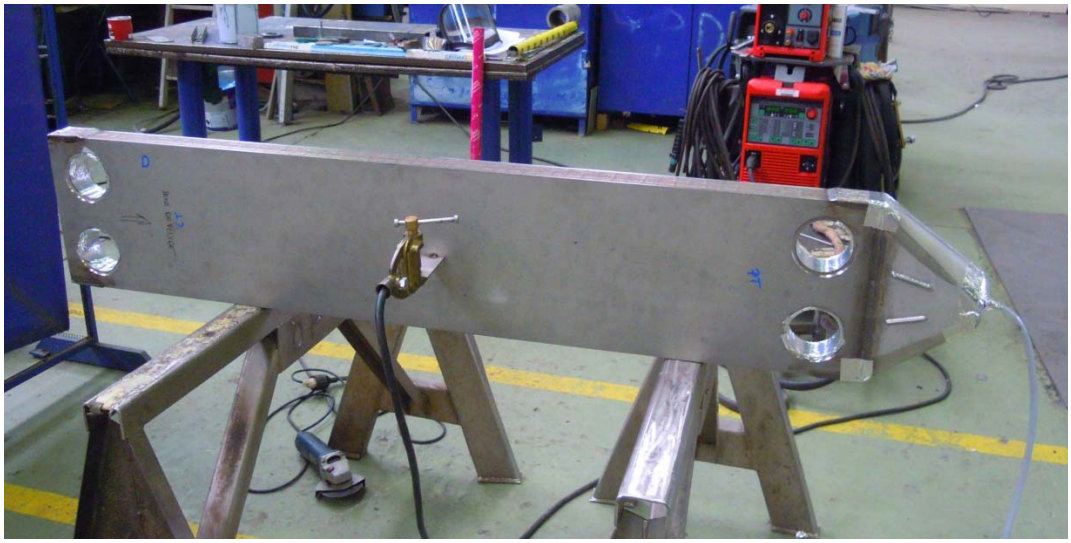
To minimize the heat losses between bundle and pressure vessel, and to have accurate results on the efficiency of bundle, the pressure vessel has been filled with wrought insulation after its installation in CEA facilities.

After welding and delivery by ALV, bundle has been equipped with headers in order to connect it to internal pipings to the pressure vessel.



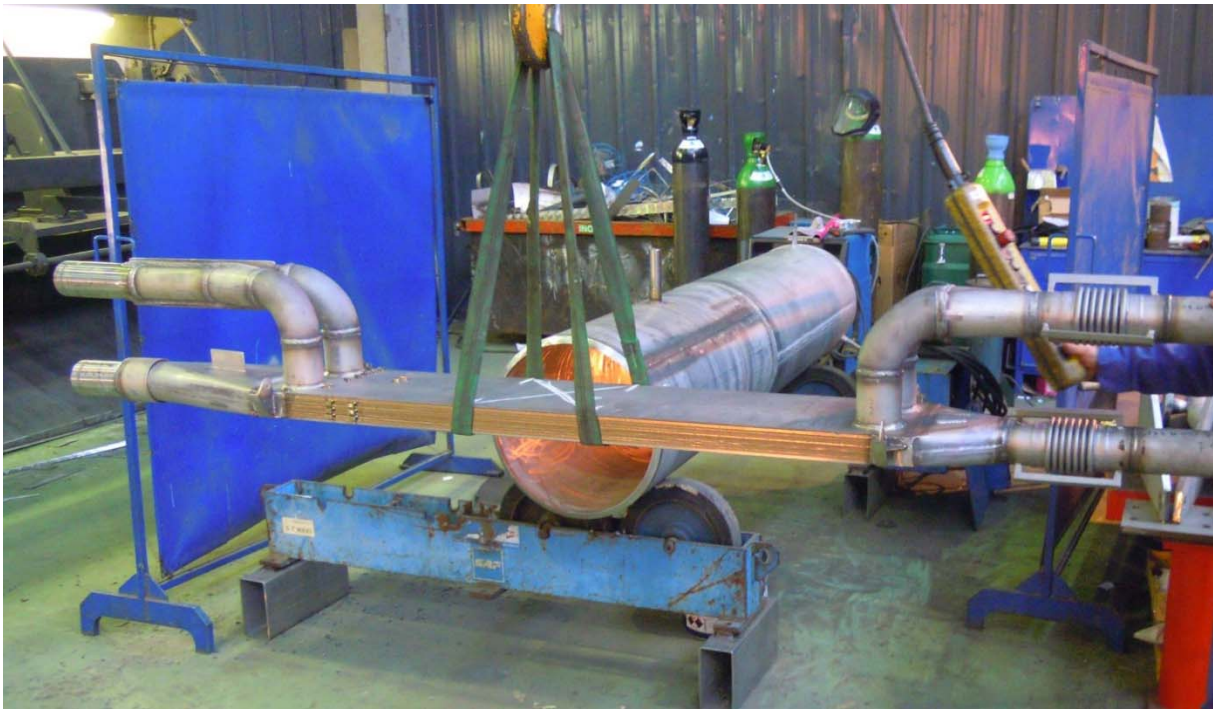
IHX bundle as welded and delivered

Bundle equiped with its headers (hot circuit)



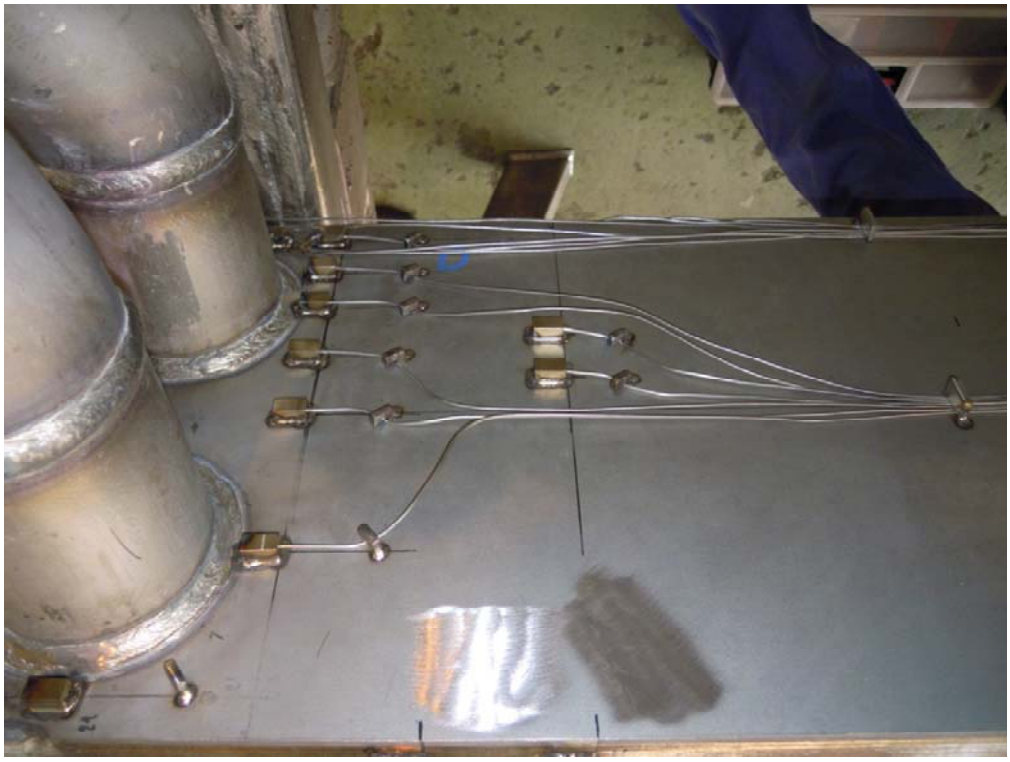
Bundle equiped with its headers (hot circuit)

After welding of headers, the welding of connecting pipes for cold circuit (welded on holes) and for hot circuit (welded on headers) has been performed. Due to the lack of space inside pressure vessel, all the welds on bundle ans its accessories had to be finished before insertion, in order to have just to weld connecting pipes to the vessel when bundle is inserted and pressure vessel is closed.

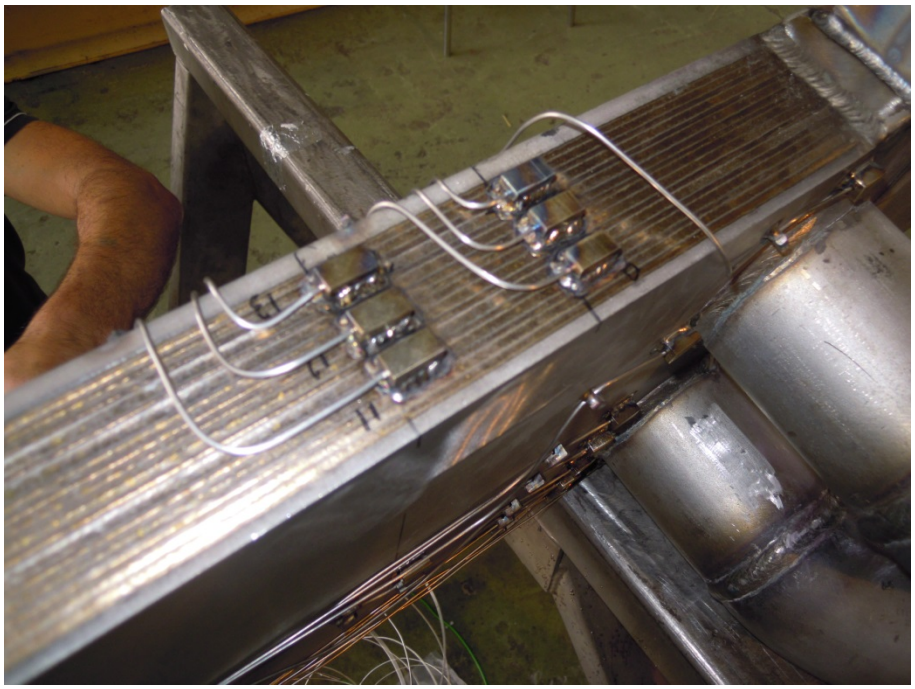


Bundle fully equipped (headers, pipings, bellows)

Prior to the insertion, bundle has been equipped with 21 thermocouples, in order to follow precisely the field of temperature obtained in the warmest and most critical part of the bundle. Thermocouples has been placed on the two external plates and on the welded wall. Thermocouples go through the pressure vessel wall by the mean

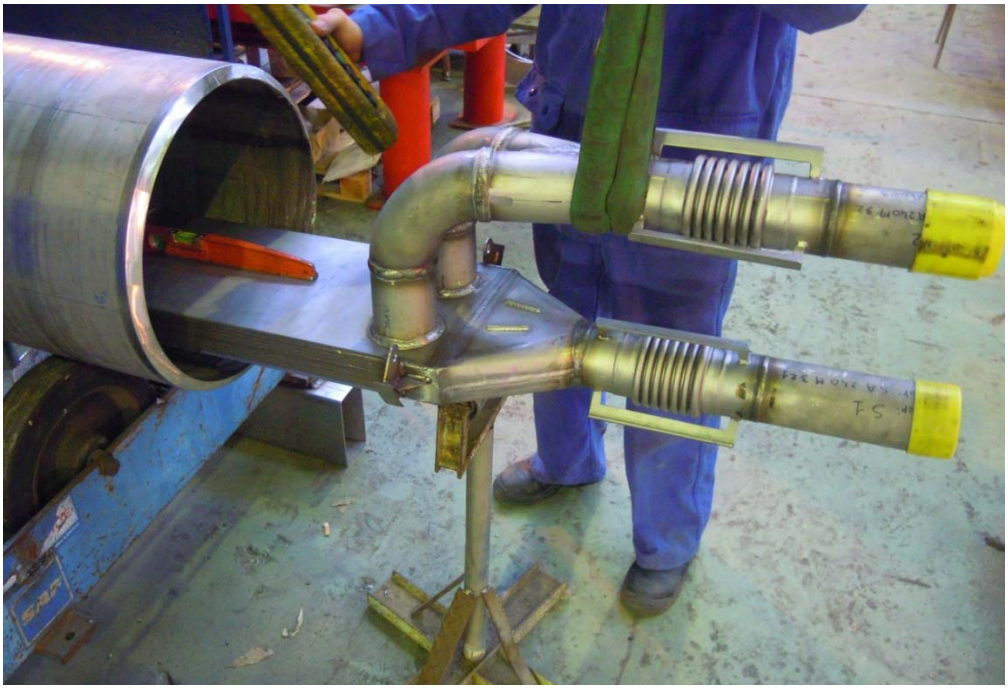


Instrumentation of bundle



Instrumentation of bundle

Then bundle has been inserted in pressure vessel, and all closing welds has been performed. Then Post weld heat treatment, Non Destructive Examinations and hydrotest have been performed before shipping of heat exchanger.



Bundle insertion

Heat exchanger complete

Integration to CLAIRE loop in CEA facilities

3. Conclusion

Such mock permitted to ALV and ALP to develop strong knowledges on high temperature heat exchangers, since current design made by ALP or ALV had to be improved to withstand to stringent operating conditions.
From a manufacturing point of view, new material and design had to be used, leading to develop new forming, machining and welding procedures.

Not common and difficult machining of thin plates has been achieved, needing to develop complex maching process and custom tools to avoid deformations. For the forming, final forming tool of the real plate was designed and tested with right forming sequence, in order to produce proper plates.
New insert design based on numerical simulations has been devlopped, without any troubles.

Some representative laser welded samples were delivered to Alstom for mechanical testing, while laser welding tool capable of welding deep in the ports was developed. Then right laser welding sequence was determined with new welding fixtures developed to optimize the welding, with the important objective to minimize the deformations.

As a result, a complete platepack was laser welded and delivered with same geometry (except height) than future IHX module for industrial application. This work proved that Alfalaval would be capable in the future to produce a bigger platepack, all laser welded with machined plates with same geometry than IHX mock up.

4. References

ARCHER Deliverable D43.11 : IHX first design – Calculation report
ARCHER Deliverable D43.41 : Test and expertise report