Feedwater heaters (FWH) are critical components in the steam-water cycle of both thermal and nuclear power plants (figure 1), where they interface between the feedwater on the tube side and condensing steam on the shell side. Because of their critical location, the performance of FWH can dramatically influence power plant efficiency and availability. The improved metallurgy, welding process and especially the Non Destructive Testing led to the continuous development of welding products for such applications. 3 main technologies of products are used for FWH’s: seamless, welded& redrawn or welded tubes. This paper will present VHET (formerly Valtimet) manufacturing process and will review what makes it special compared to other technologies. Finally typical Non Destructive Tests will be presented and their importance for all types of processes will be highlighted.

1. INTRODUCTION
Since 1970s, stainless steel material has become to be used for Low and High Pressure FWHs. Two main categories of stainless steel grades are commonly used for FWHs: ferritic stainless steels and austenitic stainless steels on which we will focus in this paper. Various austenitic stainless steels can be chosen according to the operational conditions of the FWHs:

- TP304 is the most common grade,
- TP304L is the low carbon version when extra corrosion resistance is needed but the ASME standards require to use lower mechanical properties than typical TP304 due to their low carbon content,
- TP304N are often used for High Pressure FWH as the ASME standard allows to use higher mechanical properties thanks to the addition of nitrogen,
- TP316 and its derivatives can sometimes be used when extra corrosion resistance is needed.

Typical HP stainless steel FWHs tubing have outside diameter (OD) from 15mm to 18mm with wall thickness from 1.1mm up to 3mm. Although seamless stainless steel tubes were traditionally used, welded tubes and welded and redrawn tubes have substituted seamless mainly for cost savings. In the 80s, Vallourec Heat Exchanger Tubes has developed a process to manufacture, with the highest standards, HP FWH tubes with wall thickness up to 2.11mm. Then Vallourec has upgraded its process in its Indian factory (figure 2) to manufacture stainless steel tubes with wall thickness up to 3mm.

2. VHET MANUFACTURING PROCESS FOR HP FEEDWATER HEATERS TUBES

Cold rolled strip is uncoiled and fed through a multiple stands forming mill which shape the strip into a tube. The tube is autogenously welded under an inert atmosphere with a non-consumable tungsten electrode (T.I.G). VHET has developed a technology which supports the welding bath during the welding operation to get perfect and smooth weld geometry inside and outside as well as protecting the internal surface of the tube from oxidation (figure 3)
ASTM A249 and ASTM A688 standards require performing, before annealing, a cold work operation either on both weld and base metal or on the weld metal only. This cold working is the necessary preliminary step to be done before heat treatment to ensure, through homogenization and recrystallization, similar mechanical and corrosion resistance properties of the weld as the parent metal. Today several technologies exist to fulfill this requirement (bead rolling, bead hammering, roll sinking, redrawing, etc...). VHET performs Roll Sink Anneal (RSA) operation which consists of passing the tube through a set of horizontal and vertical rolls sets performing an OD reduction until reaching the final tube diameter. The weld bead being softer than the metal base material, most of the cold work is supported by the weld as shown in figure 4.
The final step of the RSA process is the in-line annealing treatment to promote the recrystallization of the weld material (figure 5) and dissolution of ferrite. VHET performs Bright Annealing which ensures no oxidation, neither on external tube surface, nor on internal surface, thanks to an inert atmosphere protecting the tube during heat treatment (induction with an encircling coil) and cooling (by a waterjacket system).
The product is subsequently dimensionally inspected, tested through NDT controls (Pneumatic Testing, Eddy Current Testing and Ultrasonic Testing). Then the tube is bent, the bent part is stress relieved, hydraulic tested, dimensionally rechecked, cleaned and packaged with the best practices and according to customer specifications.

3. FOCUS ON EDDY CURRENT AND ULTRASONIC TESTINGS

- Eddy Current Test
Eddy Current Test (ECT) is required in ASTM standards like A688, this technology is able to detect short and volumetric strip defects or weld defects with short length (dents or slivers shown in figure 6 and 7). ECT is usually performed with encircling coils working in differential modes with a frequency set between 10kHz and 30kHz. ASTM A688 specifies standard defect with a drilled hole of 0.8 mm diameter with a rejection criteria according to the ASTM A1016 specifying that a tube which is producing test signal equal or greater than the lowest signal produced by the reference standard shall be designated suspect (i.e. K value = 1). In some cases more stringent criteria can be chosen like the supplementary requirement S1 of the ASTM A688.

![Figure 6: Weld dent rejected with ECT](image)

![Figure 7: Weld dent rejected with ECT](image)

- **Ultrasonic test**

Ultrasonic tests are generally done in the longitudinal direction to detect long and longitudinal weld defects, like lack of penetration or weld mismatches.

Common standard defects used are longitudinal notches U shape, 10 or 12.5% the nominal tube wall thickness in depth, 0.2 mm in width and 12.7 mm long. These artificial defects have to be located in the weld for better welding defect detection.

The sensitivity used for the austenitic tubes is $K= 0.8/0.9 (-2/-1 \text{ dB})$.
Although Ultrasonic Tests are not mandatory in the ASTM A688, it is highly recommended to perform them due to relatively severe operational conditions of High Pressure FWHs (high pressure and high temperature).

Indeed several trials have been carried out in order to check if the UT inspection can be substitute by ECT with severe parameters like the S1 supplementary requirement of A688 or S3 but the results were negative. Even with high level of sensitivity, it was impossible to detect defects like lack of penetration or edge mismatches. These defects are typically long defects and are only detected with ultrasonic test.
Even welded and redrawn tubes which are sometimes considered as higher quality product have to be controlled with UT because critical defects can occurred as shown in figure 11.

![Figure 11: Edge mismatch on redrawn tube](image)

4. CONCLUSION ON WHAT MAKES THIS PROCESS FOR HP FWH TUBES SPECIAL

- No Carbon Pollution

One of the first advantages of VHET’s process is that it does not use any lubricant inside, neither during the forming, nor during the sizing. Thus, the process guarantees the tube will not be carbon polluted during the annealing. On the contrary, the redrawing process uses lubricant for the cold work operation, imposing a degreasing of the tubes before the annealing, a really delicate operation considering the length of the tubes (more than 15m) and their small inside diameter (around 10mm).

![Figure 12: A262 practice A corrosion test :intergranular carbide precipitation](image)
• **Low level of residual stress**

With redrawing process, the straightness of the tube is not satisfactory after off line annealing in continuous furnaces. The tube must therefore be passed through straightening machines with hyperbolic rotating rolls. This operation induces deep marks on the outside surface of the tube and high residual stresses that may impair stress corrosion cracking resistance (SCC). 304 grade is very sensitive to this mechanism of corrosion particularly owing to high temperature and pressure. Consequently, the residual stress must be limited. With VHET’s new process, the tube is kept perfectly straight during annealing. Thus, this straightening operation is redundant and the level of residual stress is low.

• **No chromium depletion or overpickling risk**

When air annealed is performed, the tube has to be pickled in order to remove the oxide scale and the chromium depleted layer. This operation is very difficult on the inside surface of the tube due to the small inside diameter and the long length of the tubes. Poor pickling condition may lead to insufficient removal of the chromium depleted layer or overpickling (see figure 13). Overpickling increases the roughness of the surface and consequently increases the pressure drop. VHET bright annealing process avoids all these risks. Without pickling VHET process is environmental free (no nitrates containing waste) and safe (no HF acid involved).

![Image](image)

Figure 13: overpickling of tube inside surface

• **Stringent Non Destructive Tests**

ECT is a standard in the tube manufacturing norms but the UT should also be mandatory in order to reject critical defects that can’t be detected with other NDTs. Those critical defects could end up in tube failures and generate serious issues with the equipment especially when high pressure and high temperature are involved. ECT and UT are therefore highly recommended whichever is the manufacturing process of the tube.

• **Reduce handling risk**

In-line process reduces significantly handling risks that are generated by moving the tubes from one equipment to equipment. Tubes shall always be handled with great care in order to avoid any defect like dents, shocks, heavy marks or tube deformation that could become preferential site for corrosion initiation.
Figure 14: heavy marks created during handling