Progress on the design of a brazing connector for DEMO in-vessel components

Iván Fernández, Elena Rosa, Ángel Ibarra

Fusion National Laboratory, CIEMAT, Av. Complutense 40, 28040 Madrid (Spain)

The main unavailability sources in a fusion power plant will be caused by the replacement of large in-vessel components, as well as by components failure and short duration maintenance tasks and inspection processes. The development and validation of remotely operable leak-free pipe connectors for helium, water and liquid metal is a key issue for faster and more reliable replacement of in-vessel components. In this work, some advances in the design of a connector by brazing for DEMO blanket pipes are presented. A new clamping concept to stiffen the connector is proposed, although different previous works suggest the mechanical strength of the brazed joint could be enough and the clamp may not be necessary. A characterization of the mechanical behavior of the brazed joint, a CFD approach for modelling the capillary flow of the BAu-4 filler metal during the brazing process and a preliminary assessment on the issue of tritium permeation are included.

Keywords: brazing, pipe connector, filler metal, capillarity, tritium.

1. Introduction

The European Fusion Program is exploring different techniques to connect feeding pipes for in-vessel components in DEMO. One promising technique is brazing, which presents well known advantages: joint strength, sealing capability and no need of thermal treatment, among others.

A design of a remote handling (RH) compatible pipe connector by brazing was proposed in [1].

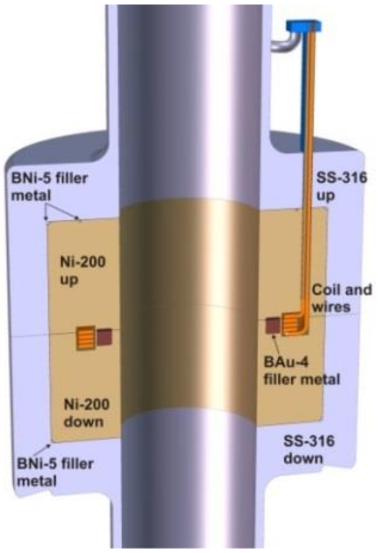

Fig. 1. Longitudinal section of the brazed connector.

The design consists of two parts, each one of which includes two main bodies: one internal made of Ni-200 and one concentric external made of stainless steel 316 (Fig. 1). The Ni-200 bodies are permanently joined to the SS-316 ones by brazing previously made in an external furnace. Induction heating in a mixture of helium and hydrogen atmosphere is used for brazing/debrazing cycles between the Ni-200 bodies, which allows vacuum sealing testing.

author's email: ivan.fernandez@externos.ciemat.es

2. Design of the clamp

2.1 Hanford Purex clamp

The brazed connector includes an external mechanical joint to increase the stiffness of the assembly. A combination of the brazed connector and the Handford Purex (H-P) clamp was proposed in [1]. Its tightening mechanism has been simplified by means of a central ring with gear profile, three jaws placed at 120º, and a spring which provides the force that ensures the strength of the assembly (Fig. 2). This simple design with few components improves the reliability of the clamp. Furthermore, the movement of the three hooks is synchronized, and the spring keeps the hooks closed at rest position, which avoids the accidental disconnection of the clamp.

A RH device concept has been also designed (Fig. 2). Its main objectives are: firstly, to connect the auxiliary systems (electric supply, coil cooling system and atmosphere & inspection system) with the connector for brazing/debrazing operations; secondly, to install/ uninstall the external clamp. A design of the interface between the RH equipment and the H-P clamp has been included.

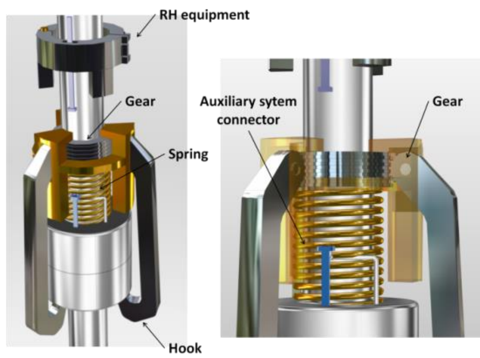

Fig. 2. Modification of the Handford Purex clamp. RH equipment and interface.

A potential issue related to the use of a spring could be the degradation of this component due to the harsh environmental conditions (high temperature and neutron irradiation) expected in the vacuum vessel upper ports, which would involve a modification in its elastic behavior.

If a shield with 20 cm thickness is used in the upper port, the neutron flux decreases from $2 \cdot 10^{12}$ to $2 \cdot 10^{11}$ n cm^{-2} s^{-1}. From these values, the fluence in the connector location has been calculated (Table 1) considering the replacement of a "starter" blanket (≤20 dpa) would be necessary after ~2 fpy; ~5 fpy in the case of a second blanket with a neutron damage capability of ~50 dpa.

Table 1. Neutron fluence in the H-P clamp spring.

Neutron flux (n cm^{-2} s^{-1})	Full power years (fpy)	Neutron fluence (n cm^{-2})
$2 \cdot 10^{11}$	2	$1.26 \cdot 10^{19}$
$2 \cdot 10^{11}$	5	$3.16 \cdot 10^{19}$
$2 \cdot 10^{12}$	2	$1.26 \cdot 10^{20}$
$2 \cdot 10^{12}$	5	$3.26 \cdot 10^{20}$

According to [2], springs exposed to a fluence of $1.3 \cdot 10^{20}$ n cm^{-2} are potentially susceptible to irradiation-enhanced stress relaxation and irradiation creep. Therefore, the only relevant case corresponds to a blanket without extra shield of 20 cm and replaced each 5 fpy.

On the other hand, several materials such as Inconel or XC 80 steel (AISI 1074-SAE) could be used to avoid spring relaxation at the maximum expected temperature in the connector (~500ºC).

In summary, both requirements (neutron fluence and temperature) seem to be separately fulfilled, although the possibility of synergic effects makes the spring performance under real conditions remains uncertain.

2.2 Quick geared triple hook concept

This concept has been designed as an alternative to the H-P clamp. As in the case of the H-P clamp, the design includes an interface with the proposed RH equipment.

The relative movement between the mechanical part of the connector and the pipe is achieved through a geared component in the pipe and gears in the head of the hooks that transfer the movement from the cover to the pipe (Fig. 3). The heads of the hooks allow free turn without turning the hook.

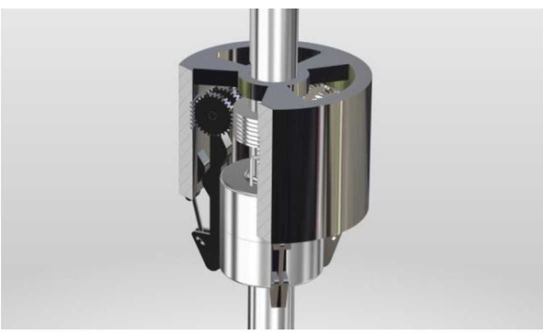

Fig. 3. Quick geared triple hook concept.

The main advantage with respect to the previous concept is that there is no spring, so the risk of failure by degradation of the mechanical properties is reduced. However, the complexity of the design with a larger number of geared components increases the possibility of jamming. A RAMI analysis would be necessary to compare the reliability of this design and the modified H-P clamp one.

3. Mechanical properties of the brazed joint and alternative filler metals

A number of variables like process atmosphere, brazing temperature and time, clearance and condition of surface affect the capillary flow of the filler metal during brazing. Consequently, the mechanical strength of the joint is also affected. Although theoretical or modelling approaches can be followed, experiments are by far the best way to optimize these features, showing that the type of filler metal is the most important factor affecting the mechanical strength of the joint [3]. Regarding this, previous experimental works show brazed joints using BAu-4 and BNi-5 as filler metals nearly keep the yield strength of the base metal, and joint failures are produced in the base metal [3], [4]. This fact implies that the external clamp can be avoided. Therefore the integrability of the connector with the environment and its compatibility with the current blanket maintenance schemes can be much better.

Other materials with similar mechanical properties at high temperature, such as Ni-Pd-Cr-Fe-B-Si alloys, could be used as filler metals, since BAu-4 is too expensive due to its high gold content (82%). The shear strength at 538ºC of brazed joints with Ni-Pd-Cr alloys was found equal or superior to those of joints with BAu-4 [5]. In addition, their joint ductility at room temperature and their corrosion susceptibility are similar to those of BAu-4 [5].

Another issue to be assessed is the possibility of suppressing the internal Ni-200 parts to directly braze the stainless steel parts. Stainless steel tends to form a chromia scale in a helium atmosphere at elevated temperatures [1]. Knowing its influence in the re-brazeability and general behavior of the joint for this specific application would be of special interest, considering that the number of brazing/debrazing cycles should be very limited.

It must be noted that high nickel content alloys like Ni-200 cannot be used as pipe material for PbLi because of the high corrosion rate, unless corrosion barriers like coatings are used. In consequence, the study of the application of this method for joining RAFM steel pipes is recommended.

On the other hand, neutron-induced swelling can occur in pure nickel. Nevertheless, some experiments show swelling can be partial or totally prevented by adding solutes like 1% Si or 0.5% Al to pure nickel [6] (Ni-200 contains 0.35% Si). Furthermore, density of dislocations and defects previous to cold-work as well as dpa rate are critical for the achieved swelling level.

3.1 Thermomechanical analysis

An electromagnetic-thermal analysis carried out in [1] showed that the induction heating process can be very fast and localized. However, the brazing process requires uniform temperature near the interface between the base metal and the filler metal to obtain suitable mechanical properties. Thus, a new electromagnetic-thermal analysis has been performed. The coil and its groove geometries have been modified, as well as the operational parameters of the induction heating system, in order to achieve a more uniform heating in the gap between the Ni-200 parts.

Despite the more uniform heating, the thermal stresses produced during the heating process could originate plastic deformation and residual stresses. These phenomena could also occur during cooling processes. For this reason, the mechanical behavior of the joint between the Ni-200 parts trough the BAu-4 filler metal has been characterized during a cooling scenario through 2D axisymmetric thermomechanical analyses with ANSYS.

The initial temperature map has been obtained from the electromagnetic-thermal analysis at the time when the whole filler metal is under its liquidus temperature (949ºC). Other temperature maps at 25 s and 120 s after the start of the cooling process have been obtained from a thermal transient analysis. The three temperature maps have been used in static structural analyses, assuming elastoplastic behavior for both materials (Ni-200 and BAu-4), which is defined by bilineal stress-strain curves. Null displacement along the longitudinal axis at the upper and lower edges of the Ni-200 parts has been imposed as boundary condition (conservative assumption), whereas the BAu-4 part has been set as bonded to the Ni-200 parts.

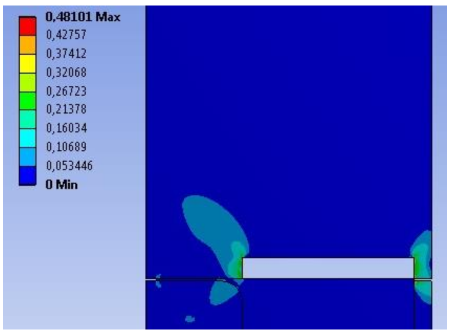

Fig. 4. Equivalent plastic strain at the beginning of the cooling process.

As expected, the results show that the initial temperature map is the most unfavorable scenario, due the higher temperature gradients. Small plastic strain mainly occurs in the Ni-200 upper part (Fig. 4), but it can be minimized by modifying the shape of the filler metal groove.

4. Modelling of capillary flow

One key issue affecting the mechanical behavior of the brazed joint between the Ni-200 parts is the spreading process of the filler metal when its liquidus temperature is reached during the induction heating. This phenomenon is mainly governed by capillary forces.

The objective of this assessment is to develop a methodology for modelling the filler metal flow along the gap, in order to optimize the spreading of the filler metal by means of modifying the filler metal groove and gap geometries.

A CFD approach can be used to model the problem as a biphasic flow with one liquid phase (BAu-4) and one gaseous phase (helium). The selected approach is based on the Eulerian-Eulerian multiphase model. Specifically, the Volume of Fluid (VOF) model is a surface-tracking technique applied to a fixed Eulerian mesh, where the tracking of the interfaces between the phases is accomplished by the solution of a continuity equation for the volume fraction of the phases. A single momentum equation is solved throughout the domain, and the resulting velocity field is shared among the phases, as well as the energy equation.

These equations are implemented and solved in ANSYS FLUENT. A preliminary 2D transient analysis has been made focusing the geometry on the gap between the upper and the lower Ni-200 parts (0.1 mm, according to the American Welding Society recommendation). The model also includes the effects of surface tension along the interface between the phases. The continuum surface force (CSF) model has been implemented here such that the addition of surface tension to the VOF calculation results in a source term in the momentum equation. The contact angles between the phases and the walls are also specified.

As viscosity values for the filler metal have not been found in literature, the used value has been obtained from Au and Ni data, whereas the liquid-vapor surface tension coefficient has been obtained from BAu-4 constituents using Guggenheim's equation.

The resulting advance of the interface between both phases which simulates the spreading of the filler metal (Fig. 5) can be compared with the obtained from the flow equation for horizontal brazing gaps [1], which is derived from Washburn's equation, in order to validate the numerical method:

$$\frac{dh}{dt} = \frac{1}{2} \cdot \sqrt{\frac{\gamma_{lv} \cdot d \cdot \cos\theta}{\mu \cdot t}} \qquad \text{(eq. 1)}$$

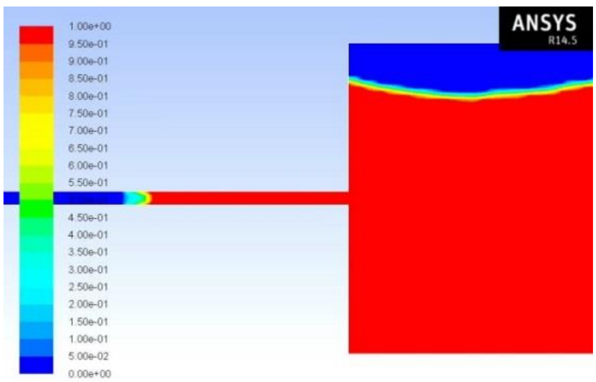

Fig. 5. Position of the BAu-4/He interface after $1.316 \cdot 10^{-3}$ s.

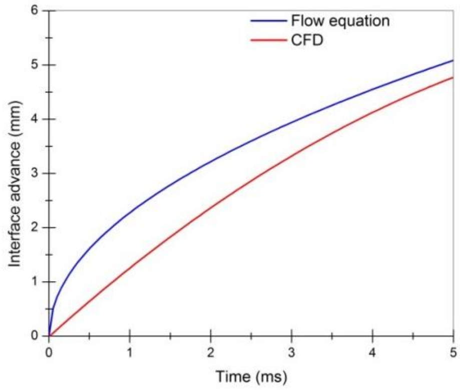

Fig. 6. Advance of the interface between BAu-4 and He.

Fig. 6 shows that the interface advance is quite similar in both cases, mainly taking into account that these results have been obtained for a short time, due to the very small time step (10^{-6} s) used for solution stability. In addition, Washburn's equation shows a good agreement with experimental data for long-time predictions, since then the capillary penetration has started to stabilize and the quasi-steady state assumption becomes more appropriate [7]. Beyond the validation of the model, this result confirms that the flow due to capillary forces is very fast at the beginning, which involves the need of an accurate control system for the heating process, as well as a careful design of the gap, the filler metal ring and its groove.

5. Tritium permeation assessment

A key requirement for pipe joining systems is to avoid tritium (T) permeation from the fluid circulating inside the pipe to the environment. Thus, a model of the connector has been created and implemented in the 1-D code TMAP7. Although Ni-200 is not compatible with flowing PbLi, the calculation has been conservatively made assuming PbLi is flowing inside at 500ºC with a volumetric flow of $3.4454\cdot10^{-4}$ m^3/s and a tritium partial pressure of 100 Pa (upper limit for HCLL PbLi pipes). The occurrence of the diffusion limited transport model has been assumed. Trapping and Soret effect have not been included, and only T is considered as diffusive specimen and T_2 as enclosure specimen. The model is focused in the central part of the connector (Fig. 7), without considering tritium diffusion across the SS-316 parts, which is expected to be negligible. Furthermore, the internal BNi-5 ring located in the upper side has been conservatively removed.

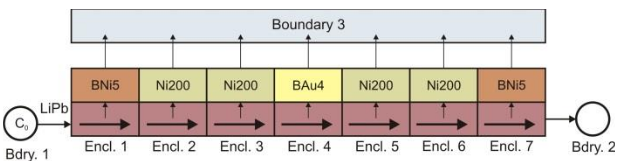

Fig. 7. Flow process diagram implemented in TMAP7.

The governing equations for the different solid segments and interfaces between enclosures and segments are the following:

$$\frac{C_{T,LiPb}}{Ks_{T,LiPb}} = \frac{C_{T,mat}}{Ks_{T,mat}} \qquad \text{(eq. 2)}$$

$$C_{T,mat} = Ks_{T,mat} \cdot \sqrt{P_{T_2,gas}} \qquad \text{(eq. 3)}$$

$$J_{T,mat} = -D_{T,mat} \cdot \frac{\partial C}{\partial x} \qquad \text{(eq. 4)}$$

No data have been found in literature about the tritium transport properties of BAu-4, BNi-5 and Ni-200 (99%Ni), so their diffusivity and solubility have been taken from their main constituents. In the case of the tritium solubility of gold, the cooper one has been conservatively used.

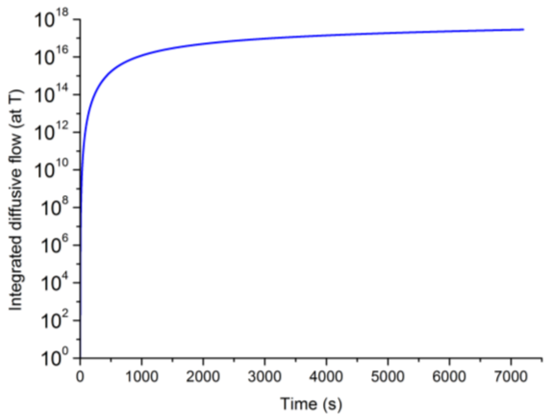

Fig. 8. Tritium integrated diffusive flow to the environment.

Fig. 8 shows that the permeation of tritium to the environment through the connector is certainly low ($4.7\cdot10^{-7}$ g/pulse), as well as the mobile inventory in the material segments after one pulse ($5.29\cdot10^{22}$ at T; 0.088 g T).

6. Conclusions

Two alternative clamping concepts to stiffen the brazed connector design for DEMO blanket pipes have been proposed, as well as a remote handling device to install/uninstall them.

Thermomechanical analyses show that the plastic strain in the zone of the brazed joint between the Ni-200 parts due to thermal stresses produced during cooling after the brazing process is small and can be minimized by modifying the design of the filler metal groove. The capillary flow of the BAu-4 filler metal during the brazing process has been modelled using a CFD approach, resulting in a fairly good agreement with the analytical model. A preliminary assessment of tritium permeation through the connector has been also made, showing that it is not relevant for this selection of materials.

Several references found in literature suggest the possibility of suppressing the external clamp, which would significantly improve the integrability of the connector. Finally, Ni-Pd-Cr alloys and other variants have been presented as alternative for the currently selected filler metals.

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