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Analysis of a tile repair technique based on brazing process for ITER First Wall

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Abstract

The European ITER First Wall panel design relies on a HIP based manufacturing sequence. However, failures of the bond to the beryllium tile might occur during the fabrication and under high heat flux qualification. A dedicated project has been stablished between UKAEA/CCFE and F4E aiming to identify suitable repair techniques.

One of the most promising identified techniques consists of a total replacement of the tile, which would be joined again with a brazing process specifically designed for this purpose. A proper replacement and repair of the tile imply a final good quality of the new bond without damaging the rest of the component. This means that the repairing brazing process has to: avoid degradation on CuCrZr base material, limit the surface beryllium tile temperature, limit the temperature and heat exposure to the neighbouring tiles, etc.

The complexity of this method has required crucial engineering analyses. The goal of the work here presented is to describe those analyses as well as the methods for finally finding the right brazing process that would be compatible with the challenging requirements. Two different approaches based on thermal assessment are proposed (supported with analytical and finite element modelling): first, a steady-state thermal analysis explores possible thermo-hydraulic conditions (via the pre-existing cooling channels) as well as the influence of the thermal contact conductance on the thermal behaviour of the component; secondly, a detailed thermal transient analysis allows reproducing in detail the brazing process following the consequences on the thermal distribution through the component.

By combining these analyses with manufacturing aspects, the right parameters controlling the process (heat flux, hydraulic conditions and braze temperature) are found. Although the predictions and conclusions require experimental benchmarking, this work has provided a strong indication of the feasibility of the proposed technique.

Keywords

ITER, First Wall, Tile, Brazing

Abbreviations

Be	Beryllium
Cu	Pure Cooper
CuCrZr	Copper Chromium Zirconium
EHF	Enhanced Heat Flux (first wall)
EU	European Union (domestic agency)
FE	Finite Element
FW	First Wall
HIP	High Isostatic Pressure (manufacturing technique)

HTC	Heat Transfer Coefficient
NHF	Normal Heat Flux (first wall)
PFC	Plasma Facing Component
RF	Russian Federation (domestic agency)
UT	Ultrasonic Test

1. Introduction

1.1. Context

The ITER First Wall (FW) component, part of the ITER Blanket system, is a key plasma facing component. It has to provide two of the key Blanket functions: cooling to accommodate high heat loads (heat flux, neutron heating and electromagnetic loads); and an adequate boundary with the plasma while minimizing the contamination impact (low influx of impurities to the plasma) [1, 2].

In order to achieve its required functionalities, the FW design includes plasma-facing units disposed on 'fingers' toroidally orientated. These fingers, 0.5-0.9 m long, are designed following to different technologies optimized for accommodating the different levels of heat loads: 'Normal Heat Flux' (NHF) technology, capable of accommodating 2 MW/m^2; and an 'Enhanced Heat Flux' (EHF) technology capable of accommodating 4.7 MW/m^2 [1]. Three procuring agencies are responsible for the design details and manufacturing routes based on their industrial knowhow and capability: NHF by Europe; and EHF by Russia and China. The work here presented is focused on NHF technology in collaboration with 'Fusion for Energy' (F4E - European Domestic Agency).

Each NHF finger consists of (see Figure 1 and [1]): 316L(N)-IG austenitic steel cooled support structure (providing a return water circuit and cooling for nuclear heating), a heat sink made of steel pipes (316L(N)-IG) and copper chromium zirconium alloy (CuCrZr); and beryllium tiles working as armour material bonded to the CuCrZr base with a copper interlayer of two millimetres. HIP manufacturing technique is chosen for bonding the multi-material structure together, with the bonds established from the Be tile to the Cu interlayer and in turn to the CuCrZr base being of critical importance to the successful performance of the panel. More information concerning NHF design and manufacturing may be found in [3-5].

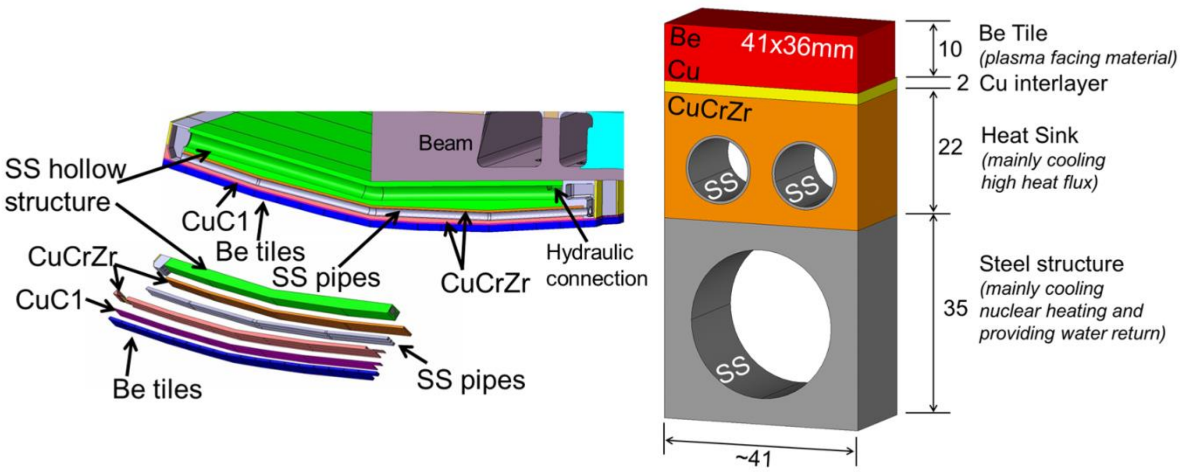

Figure 1. NHF finger structure and cross section (units in 'mm')

1.2. *Motivation and proposed repair technique*

The reliability of the plasma facing components (PFCs) is essential for proper operation of a fusion machine. The PFC operation strongly depends on the quality of the bond between the armour tiles facing the plasma and the heat sink material. Different thermal expansions of the bonded materials cause a stress distribution in the bond, which peaks at the bond edge.

Once the FW component is manufactured, it is necessary to perform quality checks that will definitely confirm its acceptability following the specifications. More precisely, failures of the bond to the beryllium tile might occur during the fabrication and under high heat flux qualification. If an unacceptable defect is detected on the tile bond [2], an action has to be taken.

One particularly promising technique amongst several identified elsewhere by the authors [12] consists of a total replacement of the tile, which would be joined again with a brazing process specifically designed for this purpose (Figure 2). A proper replacement and repair of the tile implies a final good quality of the new bond without damaging the rest of the component. This means that the repairing brazing process has to: avoid degradation on CuCrZr base material, limit the surface beryllium tile temperature, limit the temperature and heat exposure to the neighbouring tiles, etc.

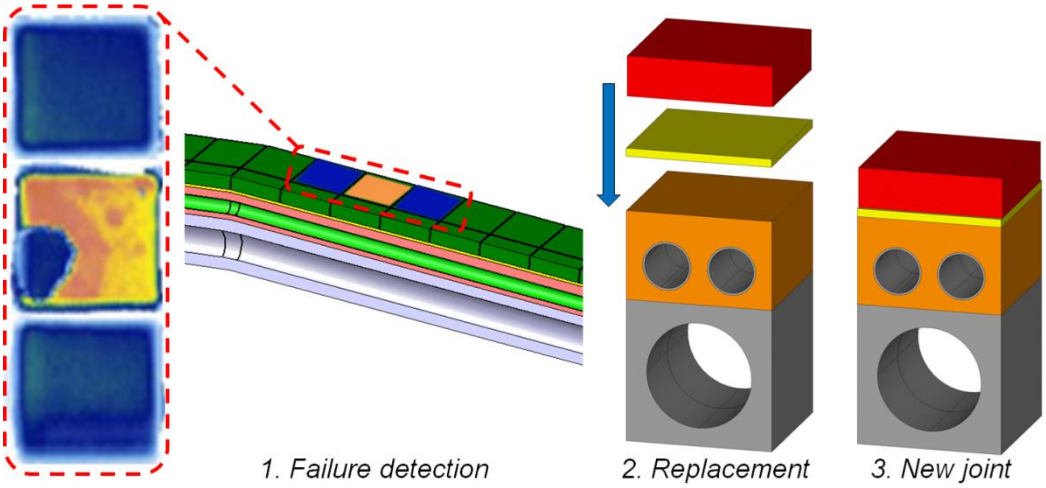

Figure 2. The three main phases of the tile repairing process

References [6-9] propose different repair techniques for different PFC concepts, where [8] and [9] are particularly relevant and propose a brazing repair option for the ITER EHF First Wall panels. EHF and NHF have crucial differences on both, design and manufacturing methods: the EHF Be/CuCrZr bond relies on high temperature brazing without an interlayer; whereas the NHF Be/CuCrZr bond relies on HIP and a Cu interlayer (as previously presented in 1.1 and Figure 1).

Due to those key differences, the method suggested in [8] for the EHF FW is not necessarily the most convenient for the NHF FW. By contrast in the case of NHF, a low temperature brazing method with gold alloy as brazing material and an electron beam gun as heating source is proposed.

The complexity of this latter method motivates the engineering analysis presented in this paper in order to better understand its feasibility. Two different approaches based on thermal assessment are suggested: first, a steady-state thermal analysis explores possible thermo-hydraulic conditions (via the pre-existing cooling channels) as well as the influence of the thermal contact conductance on the thermal behaviour of the component; secondly, a detailed thermal transient analysis allows reproduction of the brazing process in detail, providing insight into the temporal evolution of the component.

2. Parameters involved on the brazing process

The brazing process has to be designed taking into account that the component might suffer some damage due to high temperatures on materials and/or neighbouring tiles. Trying to avoid adding damage to the component, several parameters are selected as particularly relevant for designing the right repair brazing process: heat load; fluid conditions; thermal contact conductance at the interface while establishing the new bond; and finally, the braze temperature (temperature at the bond during the brazing process).

Considering the main parameters presented above, it may be concluded that designing a brazing technique mainly requires: defining heat and cooling conditions (for each step of the process); choosing the right braze material (with the required melting point); controlling the temperature at the heat sink avoiding adding damage on it and the surrounding tiles.

Each is discussed in the next subsections.

2.1. Heat load and coolant conditions

Depending on the brazing process requirements, different heat sources may be considered. The easiest would be heating the entire component in an oven or just keeping a fluid flowing through the channels at the required bonding temperature (and waiting sufficiently for the component to achieve a steady-state condition with uniform temperature).

However, as will be presented in greater detail in subsection 2.3, the heat sink material may require a non-homogeneous heat distribution on the component in order to allow the required elevated bond temperature to be achieved locally while the remainder of the component is maintained at lower temperatures. This kind of process would require a combination of heat applied to the bond, with simultaneous cooling provided by a coolant flowing with appropriate velocity and temperature through the internal structure.

Regarding what has already been explored previously for its application on PFCs, three brazing option could be considered regarding the heating method [9]: electron beam heating, direct ohmic heating and induction heating. The work here presented proposes the electron beam heating option because it allows a very local action on the damaged tile while minimizing possible damage to the surrounding tiles and materials. On the other hand, special care has to be taken with the maximum tile temperature achieved during the repairing process.

2.2. Thermal contact conductance at the interface while establishing the new bond

Another important parameter to be controlled is the thermal contact conductance between the new tile and the Cu interlayer (or between the Cu interlayer and the CuCrZr in case the tile is added with the interlayer already bonded). This thermal contact will depend on the materials in contact, the pressure keeping both surfaces in contact and the conditions of the vacuum processing environment (see Table 1). The definition of these factors is key when simulating the brazing method in order to reproduce the behaviour of the brazing material during each phase of the process: before melting, when it is melted, and finally when it has solidified again (see section 4).

A proper study in the future will require some experiments in order to know the real value of thermal conductance at the beginning of the process and how it would evolve during each phase. However, it is already possible to assume some values based on references. Those values have large uncertainty, but estimation allows useful analysis evaluating the technical feasibility of the proposed technique.

From reference [10], as mentioned in Table 1, it is possible to arrive to the next thermal contact resistances (R'') and conductances (K''):

- $R''_{t,c}$ x 10^4 = 10 (m^2K/W) → $K''_{t,c} = 10^3$ ($m^{-2}W/K$)
- $R''_{t,c}$ x 10^4 = 0.1 (m^2K/W) → $K''_{t,c} = 10^5$ ($m^{-2}W/K$)

Regarding the mentioned reference [10] (data summarized in Table 1), and keeping in mind that these numbers are just for Cu/Cu contact, three initial thermal contact conductances are taken as possible values that have to be explored: $K''_{t,c} = 10^3$; 10^4 ; 10^5 ($m^{-2}W/K$)

Contact pressure	100 kN/m^2	10,000 kN/m^2
Stainless steel	6-25	0.7-4.0
Copper	1-**10**	**0.1**-0.5
Aluminium	1.5-5-0	0.2-0.4

Table 1. Typical thermal contact resistance, $R''_{t,c} \times 10^4$ ($m^2 \cdot K/W$), for three different metallic interfaces under vacuum conditions (in bold, relevant parameters for copper) [10]

2.3. *Bond-brazing temperature*

The CuCrZr material decreases its mechanical strength when it is exposed for long time to temperatures higher than 350°C. This means that only brazing materials with low melting point (low temperature brazing techniques) would be acceptable; otherwise it would be necessary to heat too much the entire component, adding new damage on the materials.

However, even with low temperature brazing materials with a melting point around 350°C, higher bond temperature might be desirable in order to provide the right heat treatment and achieving the right bond quality at the end of the brazing process.

For the particular case of the NHF FW, gold eutectic alloys (like Au88Ge12, AuSn or AuSi alloys) has been chosen as brazing material (see reference [11]). For the studies here presented, it is considered that the melting point is about 350°C, but it is estimated that it would be needed to keep it at 500°C at least 15 minutes during the 'bonding phase' of the brazing process. Those are the temperature and time required for creating a proper bond by adding diffusion after melting the brazing eutectic alloy (see Figure 3): a gold coating on the tile would diffuse through the brazing alloy increasing the gold content and the melting point of the remaining interfacing alloy.

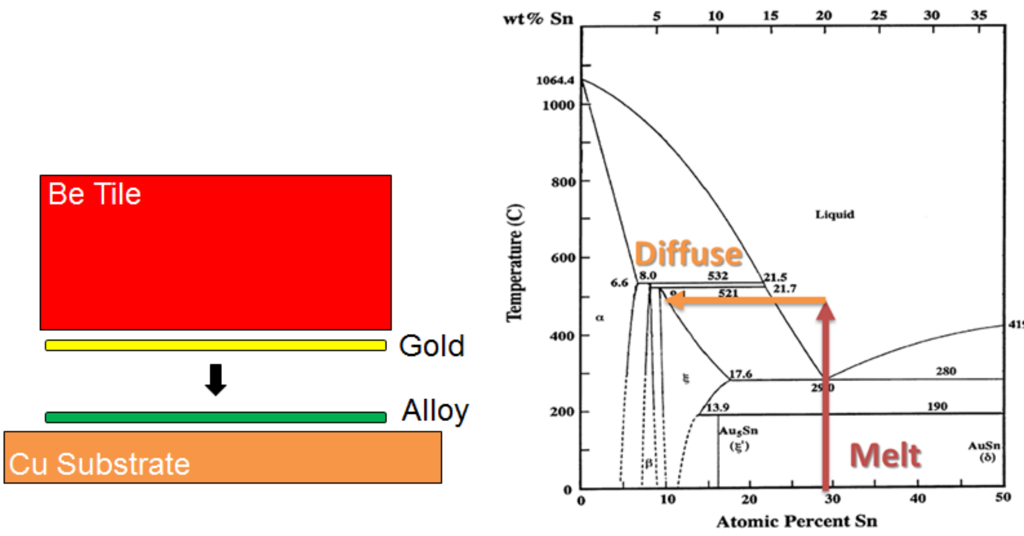

Figure 3. Sketch of the materials involved on the brazing process, and brazing alloy graph showing the evolution of the material content along the bonding process

Since temperatures higher than 350°C are required (up to 500°C), the proposed brazing process combines heating and cooling with a fluid at bulk temperature lower than 350°C (as described in section 2.1). This would allow keeping the bond at the required temperature while minimizing the volume of CuCrZr exposed to temperatures higher than 350°C.

More details about the proposed brazing process are described below. Next section 3 explores the three suggested possible initial thermal contact conductances in steady-state (as mentioned in section 2.2) under different fluid conditions and heat loads, showing how sensitive is the component behaviour to thermal contact and its link with fluid and loading conditions. Finally, section 4 will describe in detail the brazing process and will show a simulation predicting the temperature distribution on the component, suggesting the feasibility of the proposed technique.

3. Steady-state thermal model exploring options and parameters

3.1. Preliminary thermal resistance model

This study starts with a simple thermal resistance model that is useful for getting a proper understanding of the brazing process and how the key temperatures will behave. Regarding Figure 4, one section of the finger is analysed including three tiles. The failed tile is the central one and the analysis is done considering that the new bond is going to be stablished at the Be – pure Cu interface. Then, following the thermal resistance model, the maximum temperature in the copper interlayer can be calculated as:

$$T^{max}{}_{Cu} = T_{Bulk} + q \cdot \left(R_{Cu} + R_{CuCrZr} + R_{Steel} + R_{fluid}\right)$$

$$R_{Cu} = \frac{L_{Cu}}{K_{Cu} \cdot A} \; ; \; R_{CuCrZr} = \frac{L_{CuCrZr}}{K_{CuCrZr} \cdot A} \; ; \; R_{Steel} = \frac{L_{Steel}}{K_{Steel} \cdot A} \; ; \; R_{Steam} = \frac{1}{h_{fluid} \cdot A}$$

$$T^{max}{}_{Cu} = T_{Bulk} + q'' \cdot \left(\frac{L_{Cu}}{K_{Cu}} + \frac{L_{CuCrZr}}{K_{CuCrZr}} + \frac{L_{Steel}}{K_{Steel}} + \frac{1}{h_{fluid}} \right)$$

Where: T_{Bulk} is the fluid bulk temperature; q is the heat power; q'' is the heat flux; R is the thermal resistance; L the length crossed by the heat; K is the thermal conductivity of the material; A is the cross section; h is the heat transfer coefficient in the fluid.

Just by regarding the equation based on thermal resistances, it is possible to see that the maximum temperature in the copper does not depend on the thermal contact resistance (in steady-state). However, the thermal contact is key for calculating the temperature in the beryllium tile, where the maximum temperature of the entire system is achieved (and should always be less than 650°C).

Although the thermal resistance model is useful by supporting the understanding of the system, it is a too simplistic way to model it. Next, a 3D finite element thermal model is developed looking for a better understanding of the temperature distribution in the CuCrZr (see again Figure 4), which allows finding the optimum fluid conditions as well as the heat flux minimizing the impact on the component (regarding temperatures in CuCrZr and in the neighbouring tiles).

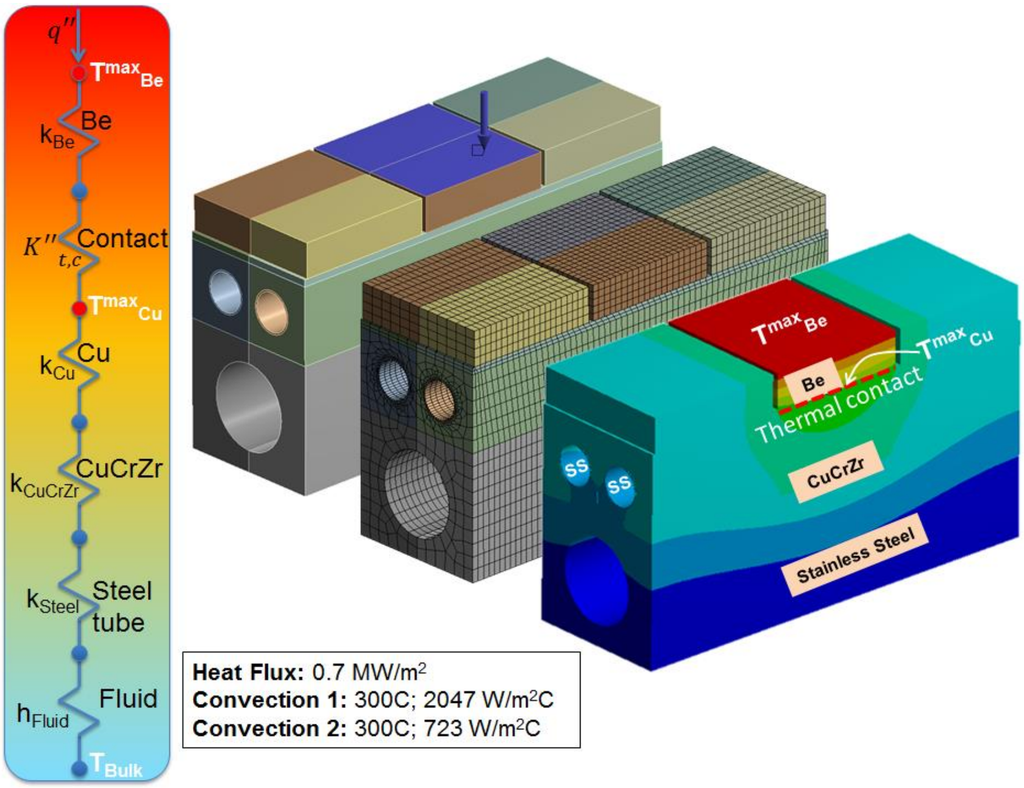

Figure 4. Thermal resistance and 3D FE models exploring bond temperatures with different loading, thermal contact and hydraulic conditions (Convection 1 & 2 defining HTC in small and large tubes respectively)

3.2. FE thermal analysis

Three finite element models with three different initial thermal contact conductances are first assessed (see Figure 4). The goal is to explore the consequences of each value trying to reduce the uncertainty around it.

For this exploratory analysis, the first idea was to keep the same working fluid as on normal operation, which is water. However, as it was described above, it has to work at quite high temperature in order to help on achieving the right temperature at the bond without using too high heat flux, otherwise we would get too high temperatures on the tile. Having 300°C as coolant bulk temperature, at a reasonable pressure (20 bar), the water would actually be steam (as would also occur for the typical NFH FW operating pressure of 40 bar): as it will be presented in section 4, the finally proposed brazing method considers nitrogen, which would simplify the process with no coolant state change on the system.

Keeping for this preliminary study steam as the working fluid in the cooling channels, the heat transfer coefficient (HTC since now) would be calculated with the Gnielinski correlation:

$$Nu = \frac{\left(\frac{f}{8}\right) \cdot (Re - 1000) \cdot Pr}{1 + 12.7 \cdot \left(\frac{f}{8}\right)^{0.5} \cdot \left(Pr^{2/3} - 1\right)}$$

$$f = \frac{0.25}{\left\{\log_{10}\left[\frac{\left(\frac{\varepsilon}{Dh}\right)}{3.7} + \frac{2.51}{Re\sqrt{f}}\right]\right\}^2}$$

$$HTC = Nu \cdot \frac{k}{D_h} \quad \left(\frac{W}{m^2\,K}\right)$$

Looking for the right fluid parameters to be used in the analysis, a large enough HTC is desirable since that helps to keep the CuCrZr temperatures close to the fluid temperature, minimizing the volume affected by higher temperatures. The next parameters are proposed for this study:

- Inlet Pressure: 20bar (T_{sat}=212.38°C)
- Inlet Temperature: 300°C (T_{Bulk}>T_{sat}: steam)
- Coolant Velocity in small pipes: 30 m/s
- Coolant Velocity in large pipe (reminding that the large pipe is the return of the two small pipes): 14.4 m/s

These fluid conditions mean that the small and large channels will perform as it is described in the next table (pipe roughness assumed as 0.046 mm):

	Small channels (D_h = 11 mm)	Large channel (D_h = 24 mm)
HTC (W/(m^2*K))	2047	723
Velocity (m/s)	30	14.42
Mass flow rate (kg/s)	0.023	0.046
Density (m^3/kg)	7.97	7.97
Reynolds number (-)	130951	121427
Prandtl number (-)	0.99	0.99

Table 2. Steam conditions

The model would be ready to run once the steam conditions, the initial thermal contact and the heat flux are well defined. For this study, it is assumed that 400°C at the bond are required in order to start the bonding process. Considering the cooling conditions presented in Table 2, it is calculated that 0.7 MW/m^2 are needed.

As a result, it is obtained the three different temperature distributions shown at Figure 5. As this assessment is performed on steady-state, the result may be interpreted as the initial thermal situation of the process, just before melting the brazing material and starting the diffusion and bonding process. Figure 5 shows that, under the assumed conditions, a thermal contact conductance of 10^3 (m^{-2}*W/K) would not keep a good enough contact between surfaces since the beginning, finding unacceptable high temperatures in the beryllium tile.

Exploring more thermal contact cases as it is shown in Figure 6, it is concluded:

- The minimum acceptable initial thermal contact conductance would be a value close to 5000 (m^{-2}*W/K)
- With an initial thermal contact conductance of 50000 (m^{-2}*W/K) the temperature distribution in CuCrZr and at the neighbouring tiles is roughly the same as with higher values, which means that 50000 (m^{-2}*W/K) may already be considered as a perfectly bonded contact.

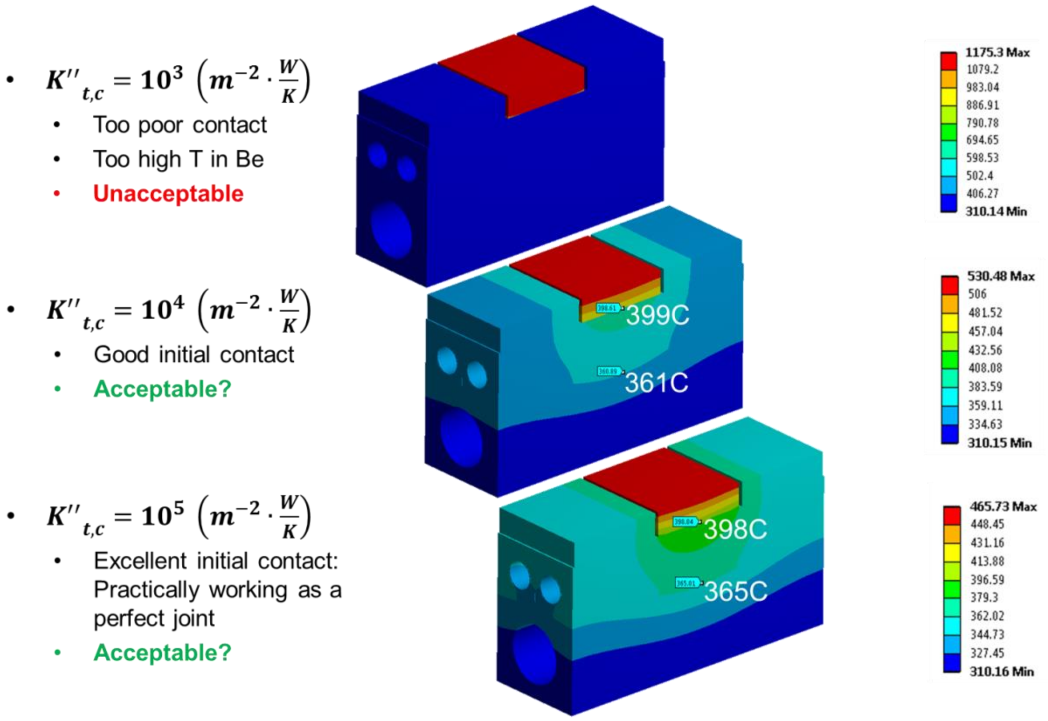

Figure 5. FE model results for different initial thermal contact conductances

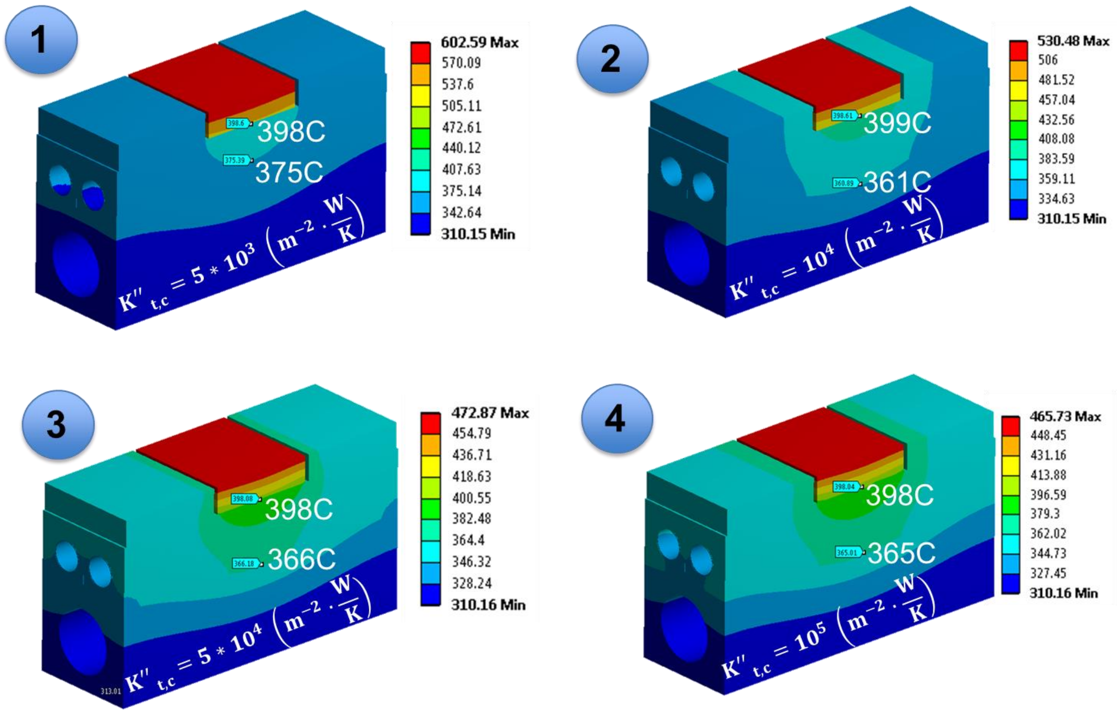

Figure 6. FE model results exploring in detail different initial thermal contact conductances

3.3. *Effect of including the clamp*

One last consideration is taken into account for this study: the brazing process requires clamping the tile applying pressure to the surface of the beryllium tile. As a consequence of that, the heat flux is not applied homogeneously on the tile surface and:

- Contact pressure is higher in the centre of the tile (good for bonding)
- Contact temperature is lower in the centre of the tile (potentially bad for bonding)

Future tests and experiments should optimize the process also from this point of view; however, some preliminary analysis may be done with the Finite Element method. This study assumes that thermal contact conductance is the same for the entire tile contact surface (which is not true due to the different contact pressure; future work could explore and include this detail in combination with data from experiments), and Figure 7 shows how the heat flux has been applied.

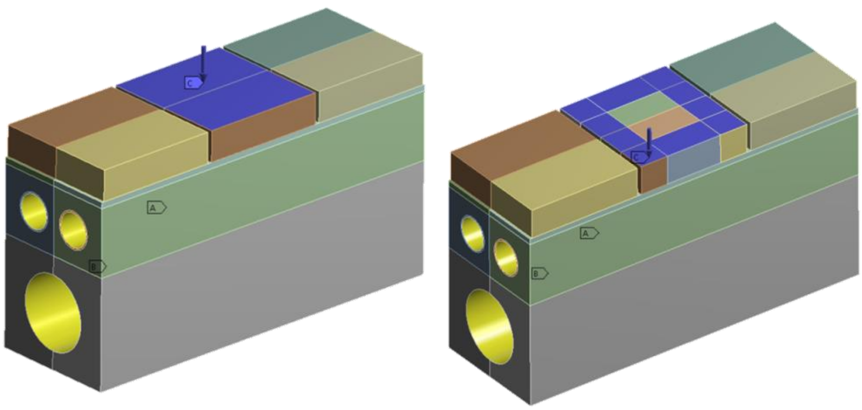

Figure 7. Heated area (indicated in blue) is reduced (comparing right to left images) when physical clamping of the tile during the bonding process is considered

The result is presented in Figure 8, comparing with the homogeneous heat flux before discussed. The two key initial thermal contact conductances above observed are analysed.

Few conclusions may be presented:

- With the same heat flux, lower temperatures are achieved when the effect of clamps are included. This is simply a consequence of the less heat transferred to the tile (less heated area)
- Higher heat fluxes would be required for achieving the same bond temperatures
- Bond temperature distribution due to clamps do not seem to be a problem: it is seen a quite homogeneous bond temperature distribution even in the beryllium side thanks to the good thermal conductivity of the beryllium tile (the heat is diffused efficiently from the tile surface to the bond)
- However, if the contact pressure changes a lot from the centre to the side of the tile (which will depend on the beryllium stiffness), the conclusion might be different: less contact pressure at the tile edges could mean less thermal contact conductance at the edges and large temperature variation along the bond

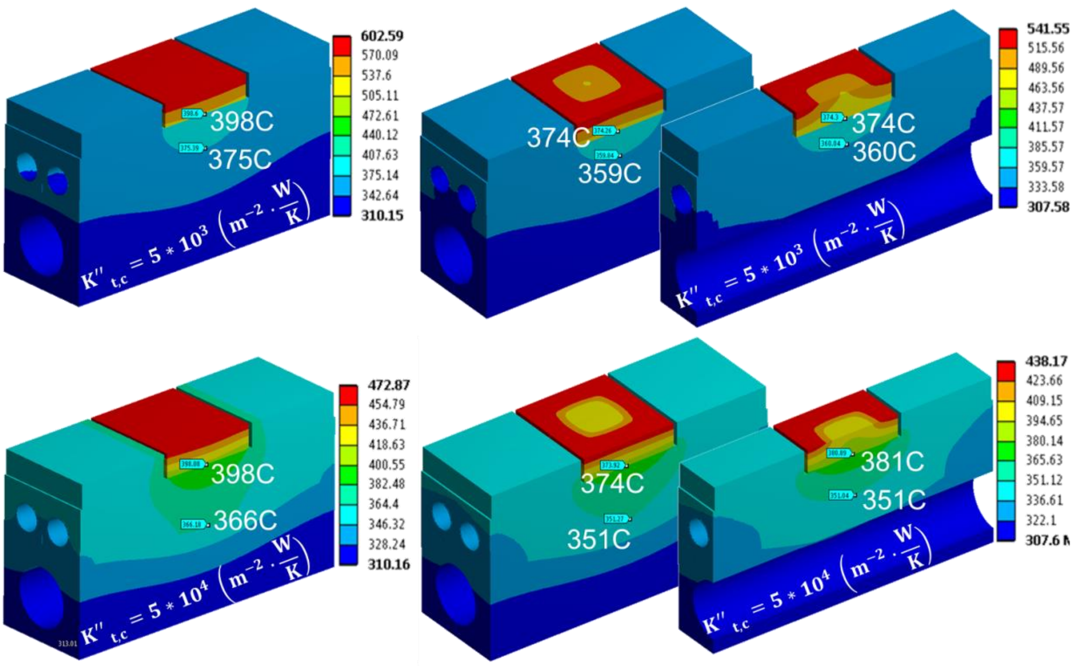

Figure 8. Thermal analysis including the effect of clamping

4. Transient thermal model simulating the brazing process

4.1. Main features and assumptions defining the brazing process

A transient analysis is proposed in order to study more in detail the actual brazing process, which has to be transient by nature. The purpose of this final study is to reproduce all the phases of the brazing process showing at the end that the low temperature brazing option would not damage the component.

The brazing process starts with a first phase of pre-heating from environmental temperature (here assumed 22°C) up to an intermediate temperature. Once the steady state is reached, the component remains around 10 minutes before starting the next heating phase that will heat the bond up to the bonding temperature. A low thermal contact is considered during the process at temperature lower than the bonding temperature (pre-heating plus main heating before reaching the bonding temperature) since it is assumed that no real bonding has started yet. However, once the bonding temperature is reached, the brazing alloy is melts very quickly. As a consequence of this, a perfect bonding contact may be modelled once the bonding process starts.

The next list of characteristics describes the studied brazing process:

- Low temperature brazing with gold alloy as brazing material
- Bonding temperature: 500°C
- Fluid: nitrogen instead of steam, since it is easier to heat from 22°C to 300°C (no change of phase)
- Preheating is done without electron beam. Since nitrogen is at 300°C, the steady state is reached at that temperature
- Heating during bonding phase done with electron beam gun without heating the centre of the tile where it is clamped
- Heating-bonding phase requires 15 minutes once the steady state is reached: 10 minutes melting time and 5 minutes diffusion time

In order to reproduce the process as realistically as possible, next considerations are taken for the simulation:

- N_2 conditions (pressure 15 bar and velocity between 10 m/s and 20 m/s in small channels) and heat flux (1.1 MW/m^2) where carefully chosen in order to get the right bond temperature once the steady-state is reached. The fluid conditions are summarized more in detail, for the three channels, in the next Table 3.

	Small channels (D_h = 11 mm)		Large channel (D_h = 24 mm)	
T (°C)	22	300	22	300
P (bar)	15	15	15	15
HTC (W/(m^2*K))	792.1	821.5	274.3	289.3
Velocity (m/s)	10	19.60	4.20	8.24
Mass flow rate (kg/s)	0.0163	0.0163	0.0326	0.0326
Density (m^3/kg)	17.18	8.76	17.18	8.76

Table 3. N_2 conditions

- Thermal contact evolves during the simulation, being very low before the bond is established, and excellent when it is supposed that the bond is well stablished (bond temperature reaching 500°C). The FE model includes this effect by modelling a dependency of the thermal contact conductance with the bond temperature

- The simulation reaches the steady-state of the three processes: preheating (300°C), heating (500°C) and cooling (22°C). Once the steady state is reached, the model does not wait the total time that the real brazing process would need (10 minutes preheating and 15 minutes heating), since that would not add new information (just constant temperature running on time)
- 2 seconds is assumed as enough for increasing or decreasing the N_2 temperature when the electron beam gun is not working (from 22°C up to 300°C; from 300°C down to 22°C). This value is probably unrealistically short, but it does not affect the final result. A longer time would just add time to the whole simulation without adding new information or improving the interpretation of the result

Figure 9 presents a sketch summarizing the process and the simulation respectively. More details about how the simulation is done at each step may be mentioned:

- **Step 1:** 2 sec. increasing N_2 temperature from 22°C to 300°C (this 2 sec. is an assumption; the actual required time depends on technology capability); low thermal conductance (5000 m^{-2} W/K); time step 0.5 sec.
- **Step 2:** 498 sec. reaching 300°C at the bond; low thermal conductance (5000 m^{-2} W/K); time step 60 sec.
- **Step 3:** 0.1 sec. increasing heat flux from 0 up to 1.1 MW/m^2; low thermal conductance (5000 m^{-2} W/K); time step 0.05 sec.
- **Step 4:** 499.9 sec. reaching 500°C at the bond; high thermal conductance (10^6 m^{-2} W/K); time step 60 sec.
- **Step 5:** 0.1 sec. decreasing heat flux from 1.1 to 0 MW/m^2; high thermal conductance (10^6 m^{-2} W/K); time step 0.05 sec.
- **Step 6:** 2 sec. decreasing N_2 temp. from 300°C to 22°C (assumption; reality depends on technology capability); high thermal conductance (10^6 m^{-2} W/K); time step 0.5 sec.
- **Step 7:** 497.9 sec. cooling the structure; high thermal conductance (10^6 m^{-2} W/K); time step 60 sec.

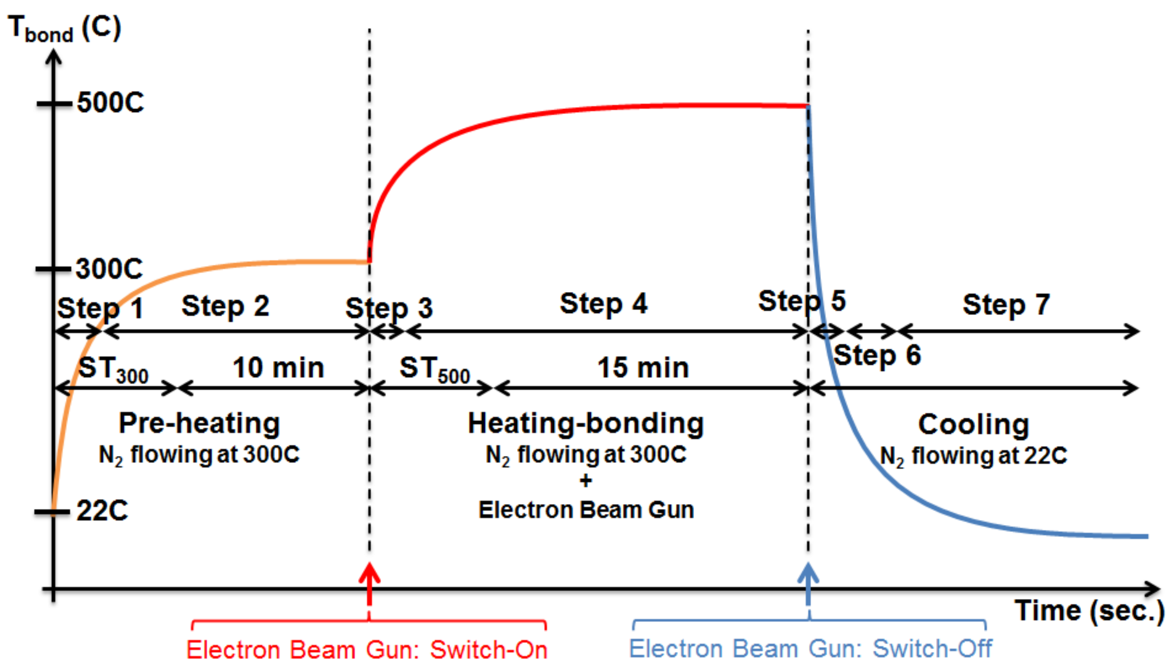

Figure 9. Sketch describing the transient phases of the brazing process in the FE simulation

4.2. Transient thermal evolution along each step of the process

Different results of the simulation at different times are collected and presented in the next Figure 10. Regarding these results, it may be mentioned that:

- The brazing process has been simulated in the most realistic possible way with the data currently available. However, possible improvements can be foreseen in the future if some complementary experiments or assessments clarify or confirm some of the assumptions (for instance: thermal contact conductances, effect of non-homogeneous pressure due to clamping in the centre, etc.)
- The process seems to be feasible: the CuCrZr is only partially affected by temperatures higher than 350°C, during a short period of time, without excessively high temperatures in the other tiles
- N_2 seems to be a good candidate for the process, but other options might be considered if it is justified and too high pressures are not required
- Heat flux and fluid conditions have been suggested and the results show that they are compatible with the requirements: acceptable temperature levels in beryllium and CuCrZr. However, other values might be explored in the future if it is necessary.

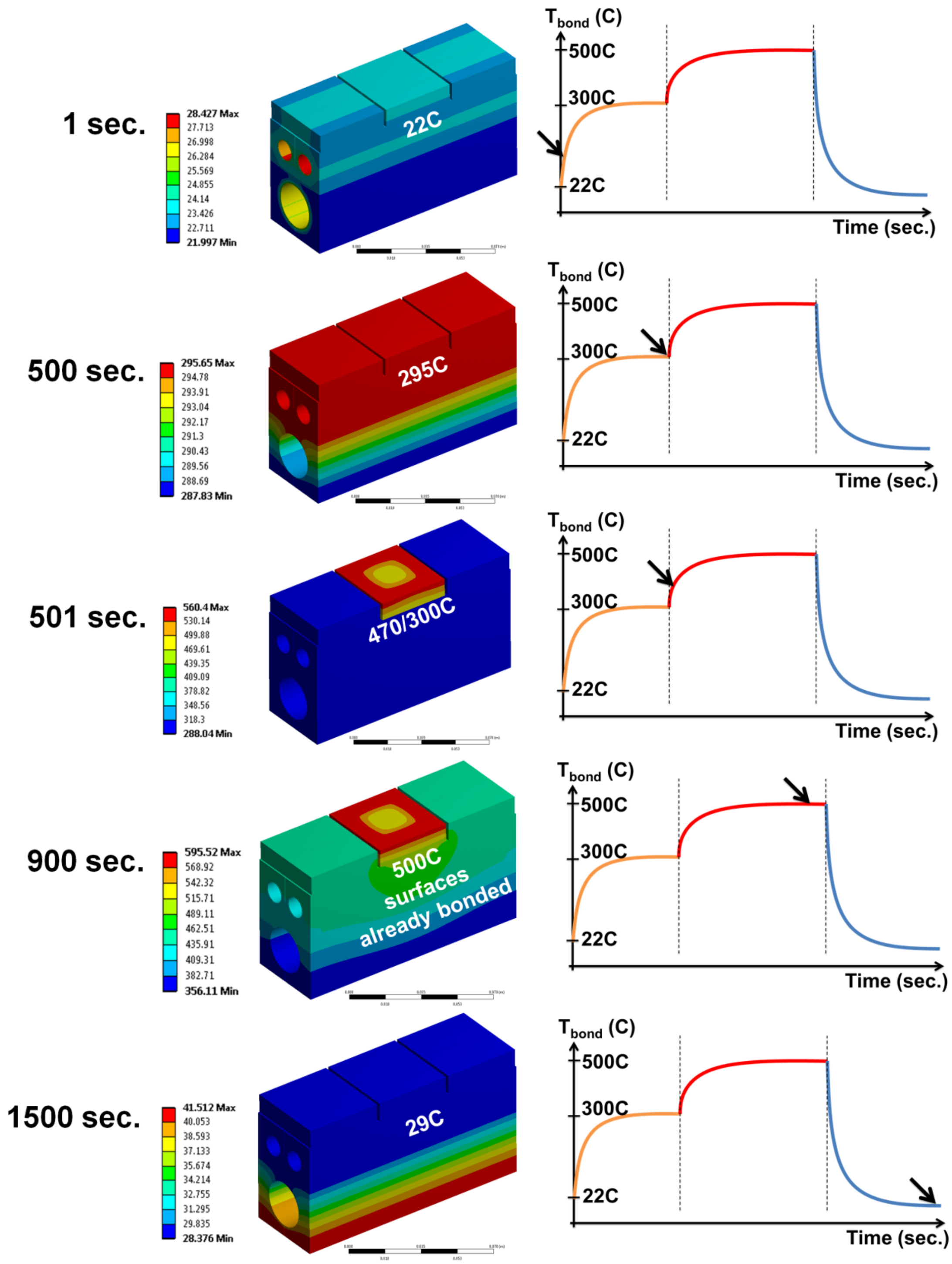

Figure 10. Simulation results at different times

5. Conclusions

A low temperature brazing process is proposed as an interesting candidate for repairing ITER NHF FW failed tiles that may be detected during the qualification of the component before accepting it for installation. Regarding the challenging operational conditions of the FW fingers in ITER, with up to 2 MW/m^2 of loading capability in the case of NHF technology, a new bonding process based on the one proposed here should be intensively investigated, with the support of comprehensive experimental studies in order to allow progressive steps towards acceptance and application.

Crucially, the study presented here shows that this kind of repair technique is feasible from a thermal viewpoint, and demonstrates that it might be done without adding new damage on the component. This result may therefore be taken as a support justifying further studies that would investigate the mechanical strength against fatigue under cyclic loading of the repaired joint.

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