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# Residual stresses in a ceramic-metal composite

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**Abstract:** The work of this study concerns the fine modelling of the thermomechanical and metallurgical behavior of interface ceramic-metal in order to determine the residual mechanical state of the structures during brazing process. For these cases, difficulties mainly arise in the modelling of the solid-solid phase transformations as well as in the modelling of the mechanical behavior of the multiphasic material. Within an original theoretical framework - generalized standard materials with internal constraints – we proposed models for the behavior of multiphasic material.

The design of joints in engineering structures and the optimisation of the industrial brazing process require determining and analysing such a phenomenon. In this way, the present work aims at predicting the thermally induced stresses (localisation and level) through numerical simulations and then, at defining the main parameters which influence their development

## 1. Introduction

Brazing is a welding process currently used to produce ceramic to metal assemblies that are interesting because ceramic and metallic materials have dissimilar thermal, mechanical, electronic and chemical behaviour. Such assemblies are integrated in complex systems designed for high technology applications (medical, aircraft, spatial, electronic or nuclear). This process allows then to link two base materials (ceramic and metal) which exhibit quite different thermo-mechanical behaviour. The difference between the thermal expansion coefficient (CTE) of these materials leads to the development of residual stresses during the cooling phase of the brazing process. Such residual stresses clearly reduce the strength of the brazed joint and can lead to catastrophic failure at the interfaces, even during the brazing process itself [1;2]. In order to perform the mechanical strength of such assemblies and optimise the brazing process, it is important to estimate these residual stresses and study the parameters that influence their development.

In particular, the materials constitutive laws, the structure geometry and the cooling conditions play a crucial role in the localisation and the intensity level of residual stresses [1]. Many analytical and numerical approaches have already been carried out to estimate such phenomenon for fixed value of these data [2-7]. In this paper, we propose a sensitivity analysis of all these factors on the residual stresses induced, which allows to define the most important ones and also to choose appropriate hypotheses for finite element models.

## 2. Brazing process

Brazing is a welding process which produces the coalescence of two or more like or unlike base materials by means of a filler metal alloy with a lower melting point. The assembly is heated to a suitable temperature upper the liquidus temperature of the filler metal which is drawn into the joint by capillary attraction. During the cooling phase, the filler metal solidification produces the joint of the base materials.

In our case, after this point (cooling from filler metal solidus temperature to room temperature), the base materials and the filler metal are not submitted to any metallurgical transformation. The two base materials are very dissimilar (ceramic and metallic part). A low thickness metallization at the ceramic surface is used to increase wettability by the filler metal at the liquid state and allow capillary attraction. The capillary attraction of the filler metal by the metallic part occurs naturally.

Heating process is realised in two phases into a controlled atmosphere furnace. First, the assembly is cooled in vacuum atmosphere to protect the metallic part from oxidation until a low cooling temperature. Then, cooling is accelerated by introducing nitrogen into the furnace at a suitable temperature to protect the ceramic part from thermal shock. The figure 1 describes the cooling conditions of the brazing process. Note that there is only thermal loading and no mechanical loading on the ceramic metal assembly during the brazing process.

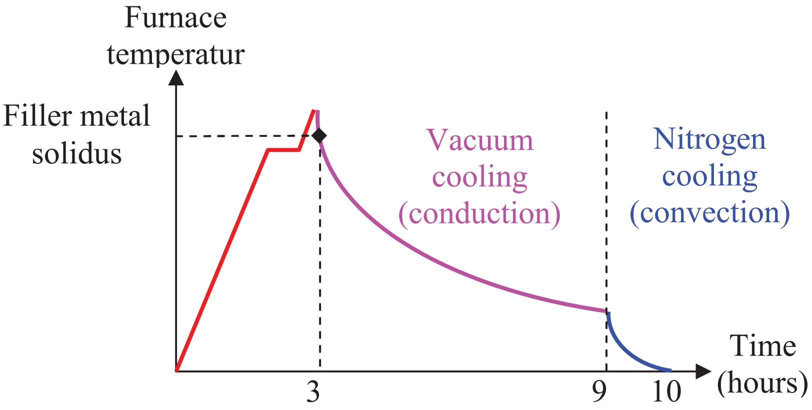

Figure 1. Cooling conditions of brazing process

The figure 2 shows the microstructure of a ceramic to metal assembly after brazing. We can observe three domains: metal, joint and ceramic. The joint is composed of the filler metal, the metalized surface of the ceramic and the interfaces generated at high temperature by diffusion between the base materials surfaces and the filler metal.

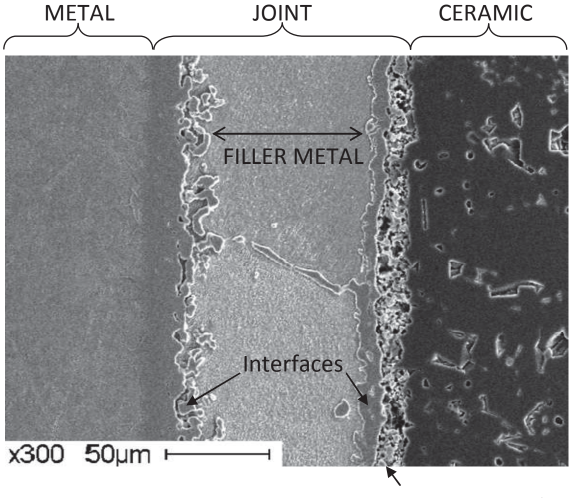

Figure 2. Microstructure of the ceramic to metal brazed assembly

## 3. Composite structure

The assembly geometry studied in this work is a 2D axisymmetric cylinder composed of three materials:

- alumina $Al_2O_3$ with a purity of 97.7% (ceramic),
- stainless steel (metal),
- silver-copper eutectic alloy (filler metal),

as the influence of other components is neglected (Fig. 3). Besides, the joined surfaces between these materials are perfectly plane surfaces.

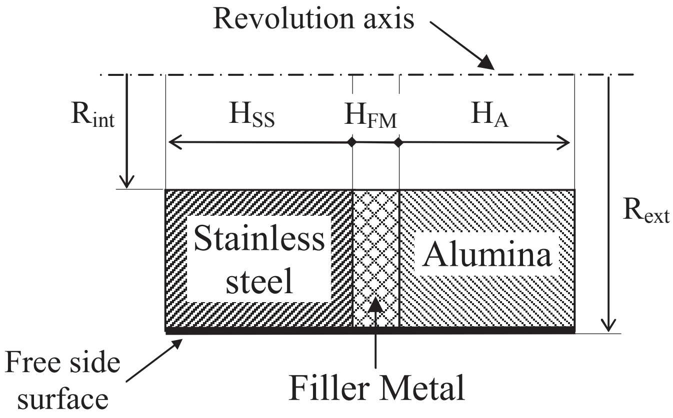

Figure 3. Geometrical parameters of the ceramic metal assembly

The geometrical parameters of such structure are the height of each component (alumina: $H_A$, filler metal: $H_{FM}$, stainless steel: $H_{SS}$) and the internal ($R_{int}$) and external radii ($R_{ext}$) of the cylinder. For a full cylinder, the internal radius value is equal to zero ($R_{int}=0$).

The ceramic material is known to be linear elastic and its properties do not depend on temperature. These parameters have been identified through ultrasonic tests at room temperature. The metal and the filler metal exhibit elastoplastic behaviour depending on temperature. Two evolutions of the filler metal yield stress with temperature, issue from two different bibliographic references [8-9], are compared to the metal one to understand the effect of this parameter on residual stresses repartition, evolution and maximum value (Fig. 4). Moreover, the impact the elastoplastic behaviour type on the residual stresses induced has also been studied by accounting constitutive laws with or without hardening for the metal material. Full bibliographic mechanical and thermal properties are available for alumina (A), stainless steel (SS) and filler metal (FM) on Table 1.

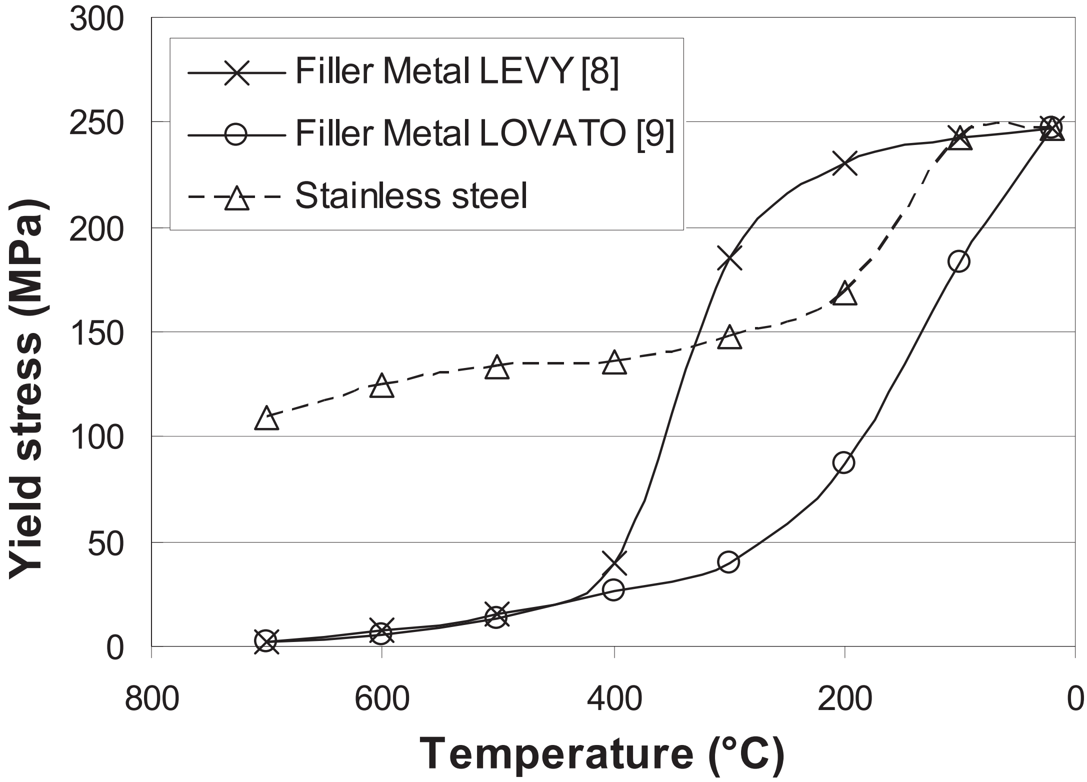

Figure 4. Metal plastic yield stress evolution depending on temperature

Table 1. Mechanical and thermal properties of each component according to temperature: Alumina (A), Filler Metal (FM), Stainless Steel (SS).

| **Young modulus (GPa)** | | | | | | | |
|---|---|---|---|---|---|---|---|
| **T(°C)** | 20 | 100 | 200 | 300 | 400 | 500 | 600 |
| **A** | 330 | 330 | 330 | 330 | 330 | 330 | 330 |
| **FM [9]** | 79 | 79 | 79 | 79 | 79 | 79 | 79 |
| **SS** | 193 | 191 | 183 | | 168 | | 148 |
| **Poisson ratio** | | | | | | | |
| **T(°C)** | 20 | 100 | 200 | 300 | 400 | 500 | 600 |
| **A** | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 | 0.26 |
| **FM [9]** | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| **SS** | 0.22 | 0.27 | 0.27 | | 0.31 | | 0.37 |
| **Coefficient of Thermal Expansion ($\times 10^{-6}$ °C$^{-1}$)** | | | | | | | |
| **T(°C)** | 20 | 100 | 200 | 300 | 400 | 500 | 600 |
| **A** | | 6.2 | 7.4 | 7.8 | 8 | 8.1 | 8.2 |
| **FM [9]** | 19.7 | 19.7 | 19.7 | 19.7 | 19.7 | 19.7 | 19.7 |
| **SS** | | 16.2 | 16.9 | 17.4 | 17.8 | 18.3 | 18.6 |
| **Yield stress (MPa)** | | | | | | | |
| **T(°C)** | 20 | 100 | 200 | 300 | 400 | 500 | 600 |
| **FM [8]** | 247 | 243 | 230 | 185 | 40 | 15 | 8 |
| **FM [9]** | 247 | 183 | 87 | 40 | 27 | 13 | 6 |
| **SS** | 247 | 243 | 169 | 148 | 136 | 133 | 125 |
| **Tensile Strength (MPa)** | | | | | | | |
| **SS** | 973 | 774 | 667 | 635 | 633 | 589 | 517 |
| **Tensile failure strain** | | | | | | | |
| **SS** | 0.48 | 0.44 | 0.38 | 0.34 | 0.35 | 0.34 | 0.34 |

## 4. Numerical model

Numerical simulations have been performed with the finite element ABAQUS code. The model is defined in accordance with the geometry chosen and the brazing process described previously:

- the structure is 2D axisymmetric;
- the mesh of the assembly has been done with an 8-node quadratic axisymmetric quadrilateral element. The element size is lowest near the interfaces and the free side surface because the residual stresses are essentially localised in theses zones (Fig. 5). A converging study on Von Mises stresses has fixed the nodes number at 6133 in our case to estimate residual stresses with a good precision;
- the rigid body displacement has been fixed (Fig. 5);
- the interfaces between the filler metal and the base materials are supposed to be perfect;

- the starting point of the simulation is the solidification of the filler metal during the cooling phase of the brazing process (Fig. 1) and the simulation ends when the ceramic metal assembly temperature is equal to the room temperature;
- there is no mechanical loading on the ceramic metal assembly;
- the thermal loading is the cooling cycle (Fig. 1) from the filler metal solidus temperature to room temperature.

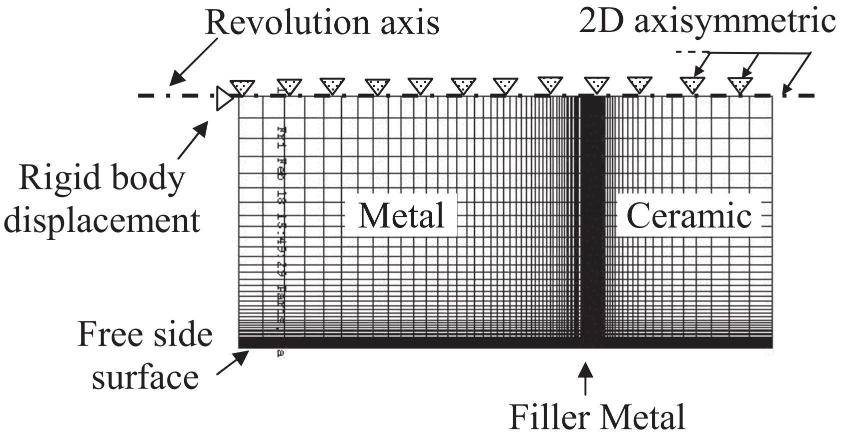

Figure 5. Mesh of the ceramic metal assembly (for the full cylinder design: $R_{int}=0$).

Moreover, two hypotheses have been studied out to get the nodes temperature according to time in the assembly:

i. Uniform cooling hypothesis: the temperature of all the nodes is assimilate to the furnace temperature according to time;
ii. Thermal analysis: two phases corresponding to the cooling process have been simulated (Fig. 1). First, the assembly is in vacuum atmosphere until a low cooling temperature, the boundary condition applied to its external surface is then the furnace temperature (conduction). Then, in a second part, the boundary condition applied to the external surface of the assembly turns into the convection flow.

The node temperatures obtained are finally introduced in the mechanical analysis to get the stress-strain response and the residual stresses. Note that the thermal and mechanical analyses are uncoupled.

## 5. Residual stresses analysis

All results show that maximum stress concentration occurs in the ceramic near the interface with the filler metal, which corroborates experimental observations [6].

### 5.1. Influence of the constitutive laws

In this part, the influence of the metallic materials (filler metal and metal) constitutive laws is analysed.

First, the importance of the plastic behaviour is studied by comparing the response obtained at the end of the cooling phase with linear elastic models and perfect elastoplastic model for both materials. In a second step, the influence of the hardening for metal is examined. Figure 6 presents the residual stress repartition along the free side surface for these different cases. It clearly appears that the behaviour of the metallic materials has a significant effect on the residual stresses obtained. In particular, the hypothesis of an elastic behaviour gives stresses values four times bigger than those with the elastoplastic models. Consequently, it seems important to take into account the plastic behaviour of metallic materials to get a coherent estimation of residual stresses. Besides, the filler metal exhibit the lowest yield value, data from Lovato [9], so the major plastic strains will occur in this material and will limit the plastic strains in the stainless steel. Accordingly, there is no remarkable difference between the results with perfect plasticity and with hardenable plasticity for the metal material. Moreover, the filler metal yield value stands as the most important material property to estimate the residual stresses values on the ceramic metal assembly.

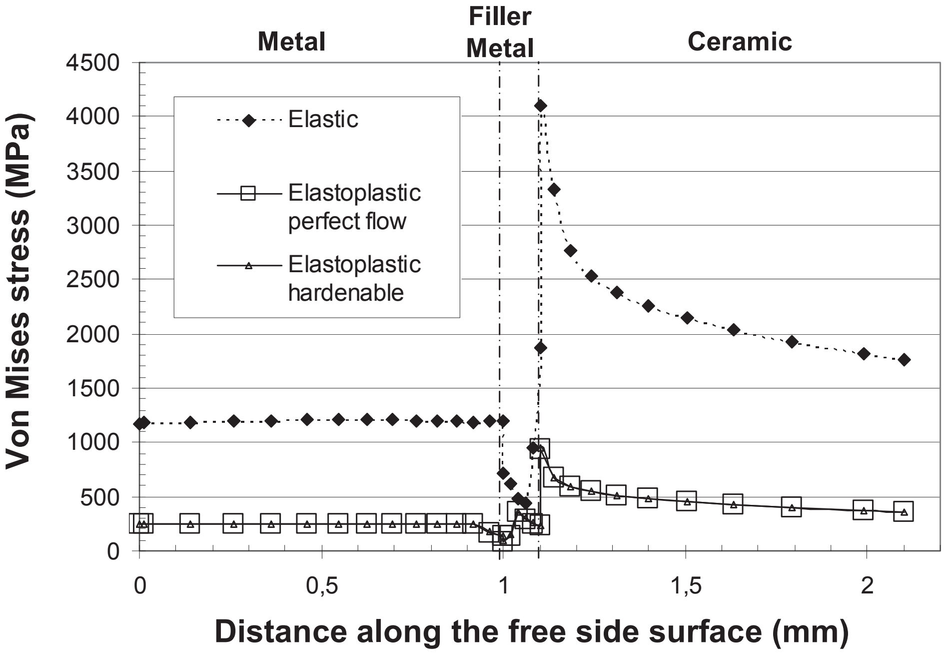

Figure 6. Residual stress distribution along the assembly free side surface according to the metallic materials constitutive laws

Let examine now the evolution of stress during the cooling phase according to the two bibliographic plastic yield stress given for the filler metal by Levy [8] and Lovato [9] (Fig. 7). For both cases, the filler metal exhibits a low yield stress value in the high temperatures range (800°C-400°C) and consequently the plastic behaviour quickly occurs. The strain induced by the thermal expansion coefficient difference between the alumina and the stainless steel part are then bigger in the filler metal part than in the other components. Consequently, the residual stresses are quite small within the assembly at high temperature because they are limited to the yield stress in the filler metal and associated to low strains values in metal and ceramic (Fig. 7).

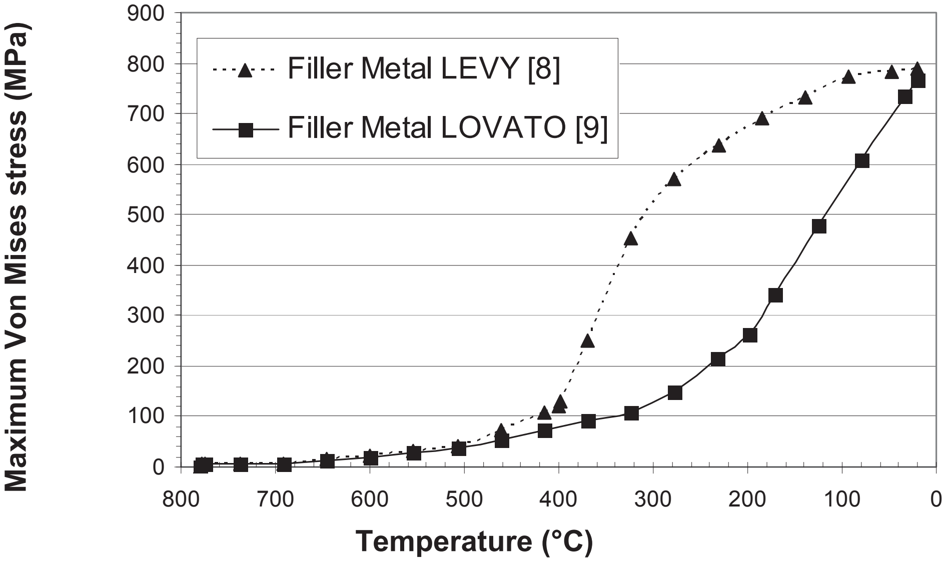

Figure 7. Maximum Von Mises stress on the free side surface according to furnace temperature and filler metal mechanical properties

In the low temperatures range (under 400°C), the yield stress value for both data increase significantly and induce bigger stresses during cooling (Fig. 7). However, the behaviour depends on the yield stress chosen. For the data given by Lovato [9], we observe the same features as for high temperature as the filler yield stress remains the significant parameter, even if its value increase with temperature. The filler metal yield stress given by Levy [8] gets upper than the metal one between 400 and 300°C (Fig. 4), so from that point, the stresses evolution follows the pattern of the metal material. Thus, we can conclude that metallic materials with yield stress as low as possible should be used in order to limit residual stresses values on the ceramic metal assemblies.

Note finally that for the two different evolutions, the residual stresses at room temperature are quite the same (maximum stress difference of 20 MPa). The yield stress evolution according to temperature seems then to have a significant impact on stresses evolution during the brazing process but not on their final values (residual stresses).

### 5.2. Influence of cooling conditions

In this part, we compare the results obtained for the two thermal loading hypotheses (uniform cooling, conduction and convection flow).

Figure 8 presents the maximum thermal gradient induced in the ceramic metal assembly for the second hypothesis, which is obtained at the beginning of the cooling phase (furnace temperature equal to 740°C). As this gradient remains quite negligible (<5°C) all along the cooling, stresses responses with both hypotheses are quite similar, during the process (Fig. 9) and at the final stage (residual stresses on Fig. 10). The uniform cooling hypothesis seems then sufficient for the numerical thermal analysis.

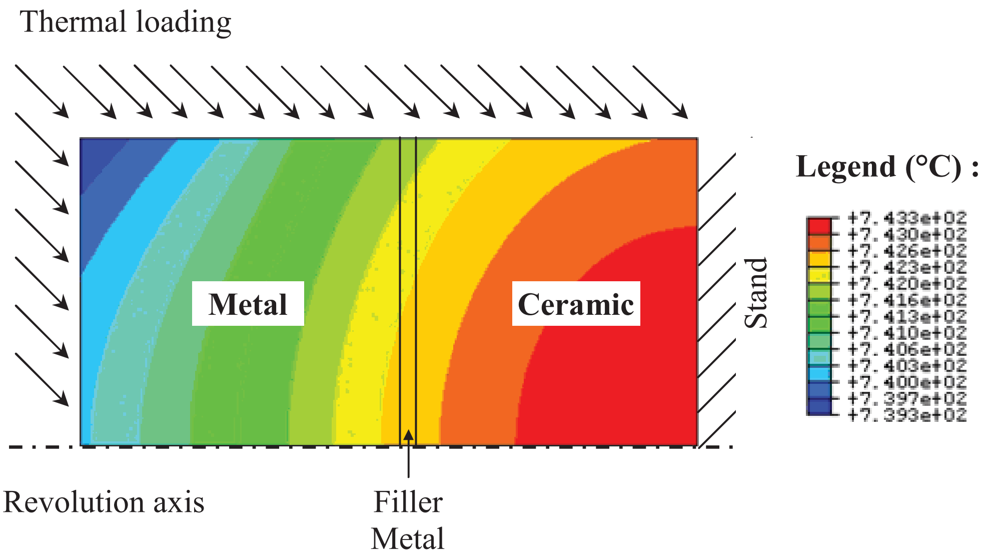

Figure 8. Maximal temperature gradient in the ceramic-metal assembly from the thermal analysis

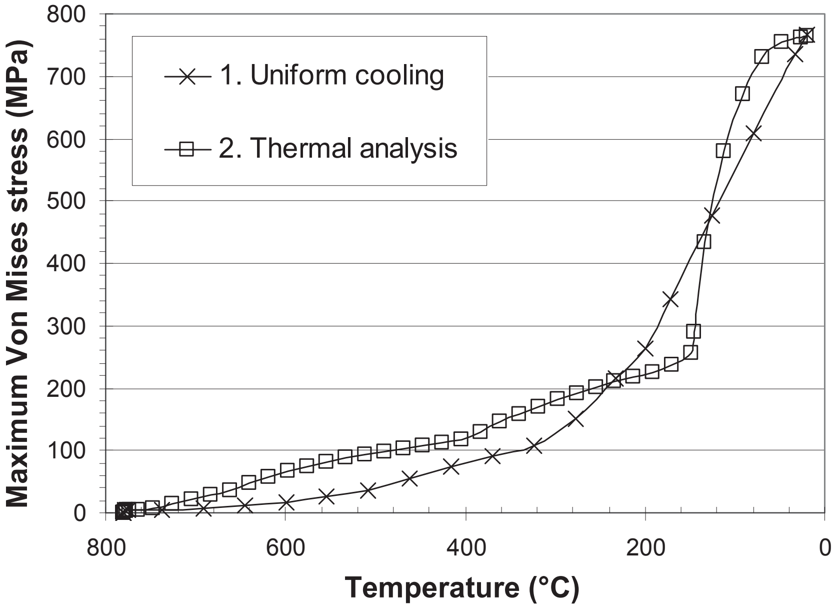

Figure 9. Maximal stress evolution according to furnace temperature and cooling conditions

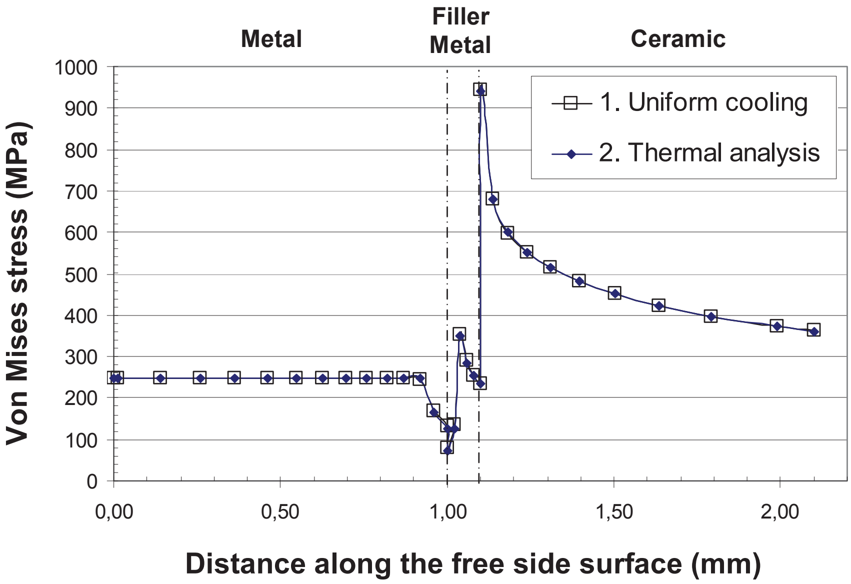

Figure 10. Residual stress distribution along the free side surface depending on cooling conditions

### 5.3. Influence of geometry

Geometrical effects on residual stresses are carried out with two-level factorial analyses.

First, a study has been performed for the full cylinder design ($R_{int}=0$) where the maximum Von Mises stress value in the ceramic-metal assembly is calculated for sixteen different assembly models where four factors (heights of each component: $H_A$, $H_{FM}$, $H_{SS}$, external radius of the cylinder $R_{ext}$) are each assigned to two levels (-1,+1) (Tab. 2). On Figure 11, we observe that if the alumina height ($H_A$) and the external radius ($R_{ext}$) are increased, the stresses in the assembly increase significantly. On the other hand, an increase of the filler metal ($H_{FM}$) and stainless steel ($H_{SS}$) heights induce a small decrease of the stresses.

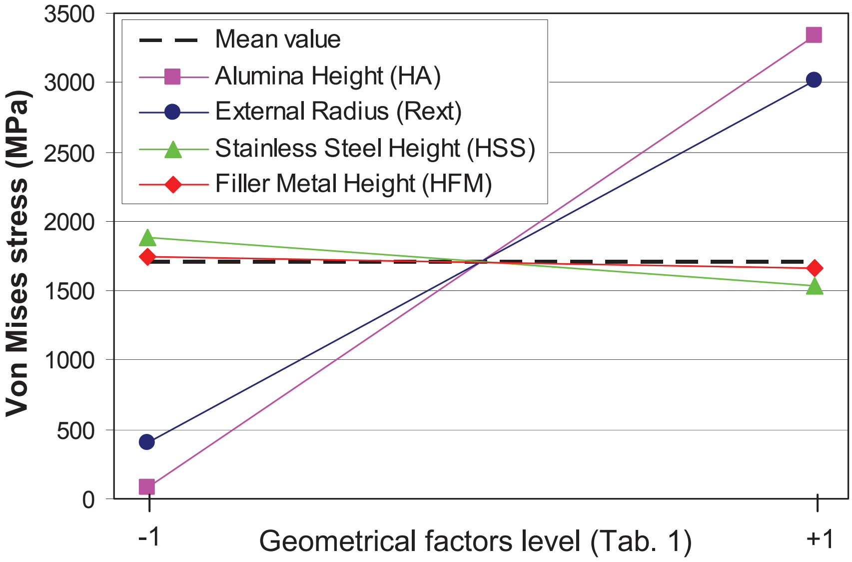

Figure 11. Geometrical factors effects on maximal stress of the full cylinder design

These results are correlated by existing data [7]. In order to reduce the residual stresses in ceramic-metal assemblies, it is then recommended to take $H_A$ and $R_{ext}$ as small as possible and $H_{SS}$ as big as possible, as the filler metal height ($H_{FM}$) is usually limited by the brazing process.

A second factorial analysis has been done for the pipe design ($R_{int}\neq 0$) with a fixed filler metal height ($H_{FM}$=0.1mm). The factors considered in this case are the heights of base materials ($H_A$, $H_{SS}$) and the pipe thickness ($R_{ext}$-$R_{int}$) of the cylinder (Tab. 2).

Table 2. Geometrical factors level (mm): a) full cylinder design – b) pipe design

| **a)** | **-1** | **+1** | **b)** | **-1** | **+1** |
|---|---|---|---|---|---|
| $\mathbf{R_{ext}}$ | 15 | 30 | $\mathbf{R_{int}}$ | 6 | 8 |
| $\mathbf{H_{SS}}$ | 10 | 20 | $\mathbf{R_{ext}}$ | 10 | 14 |
| $\mathbf{H_{FM}}$ | 0,05 | 0,15 | $\mathbf{H_{SS}}$ | 20 | 40 |
| $\mathbf{H_A}$ | 10 | 20 | $\mathbf{H_A}$ | 20 | 40 |

Figure 12 shows that the latter parameter is the most important factor which controls the residual stresses level in the assembly. Indeed, the influence of alumina and stainless steel heights is quite negligible. For this geometry, it is then necessary to limit as much as possible the pipe thickness of the cylinder.

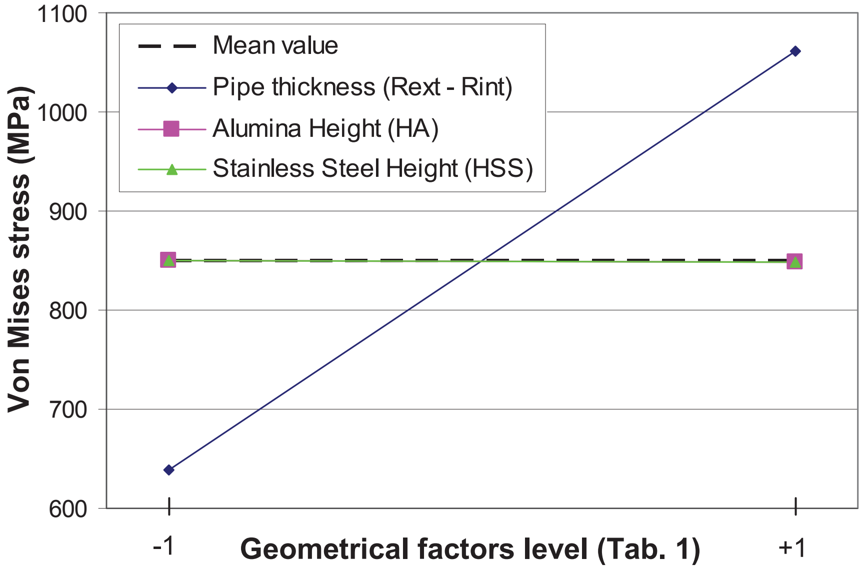

Figure 12. Geometrical factors effects on maximal stress of the pipe design

## 6. Conclusion

This paper has studied, through a numerical approach, the different factors that influence the stress development and their final value on ceramic metal brazed assemblies. These numerical results are in accordance with experimental observations on such pieces, by predicting for example the localisation of the maximum stress in the ceramic near the interface with the filler metal.

In ceramic-metal assemblies, the thermo-mechanical behaviour of the components and especially the plastic contribution of metallic materials have a significant influence on the residual stresses repartition and their maximum values. Stresses evolution during the cooling is controlled by the metallic material (filler metal or metal) that exhibit the lowest yield stress value. In order to reduce the residual stresses in ceramic metal assemblies, it is then recommended to choose metallic materials with the highest ductility.

On the numerical point of view, the uniform cooling is the most appropriate hypothesis for the thermal analysis of the brazing process as the thermal gradient between the external surface and the centre of the assembly is quite negligible.
Finally, we have shown that the optimisation of ceramic metal assemblies requires minimum alumina height and external radius for full cylinders, and minimum pipe thickness for the pipe design.

Numerical simulation of the brazing process could be improved with a more complete modelling of the interfaces between the base materials and the filler metal. It may be also interesting to account for the brittle damage that affects the ceramic material and the creep behaviour of the filler metal that occurs at high temperature.

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