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Residual stresses in ceramic metal assembly after brazing process

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Abstract. The framework of this study is the thermo-mechanical analysis of the brazing process of ceramic metal assemblies. The thermal expansion gradient between ceramic and metallic materials leads to the development of residual stresses during the cooling phase of the brazing process which induce consequently an important reduction of the strength of these composite structures. In the present work, numerical simulations are performed in order first to predict the residual stresses distribution after the brazing process and in a second step, to study their influence on the tensile strength of metallized ceramic seals. Results obtained are compared with experimental tests.

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]. Many analytical and numerical approaches have already been carried out to estimate the residual stresses within ceramic metal assemblies [2-8]. In order to define the mechanical strength of such assemblies, it is important to estimate these residual stresses. This paper aims first at determining through numerical simulations the residual stresses induced by the cooling phase of the brazing process within standard tensile specimens of ceramic metal assemblies. Then, these additional stresses are taken into account to determine the consecutive bond strength of such composite structures for standard tensile tests [9]. Numerical and experimental results are compared and discussed.

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. Besides, the two base materials (ceramic and metal) are very dissimilar. 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 then naturally.

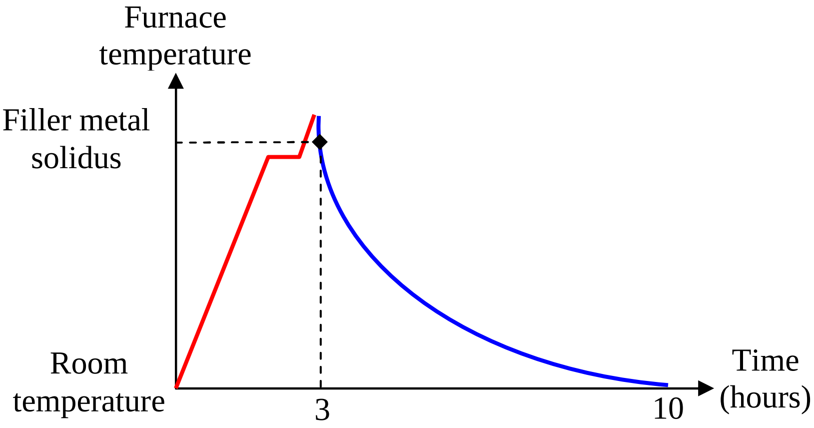

Figure 1. Thermal cycle of the brazing process

Heating process is performed in two phases into a controlled atmosphere furnace. The assembly is heated in vacuum atmosphere to protect the metallic part from oxidation. The heating and cooling rate is defined to protect the ceramic part from thermal shock. The figure 1 describes the thermal cycle of the brazing process. Note that there is only thermal loading and no mechanical loading on the ceramic metal assembly during the 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 metallized surface of the ceramic and the interfaces generated at high temperature by diffusion between the base materials surfaces and the filler metal.

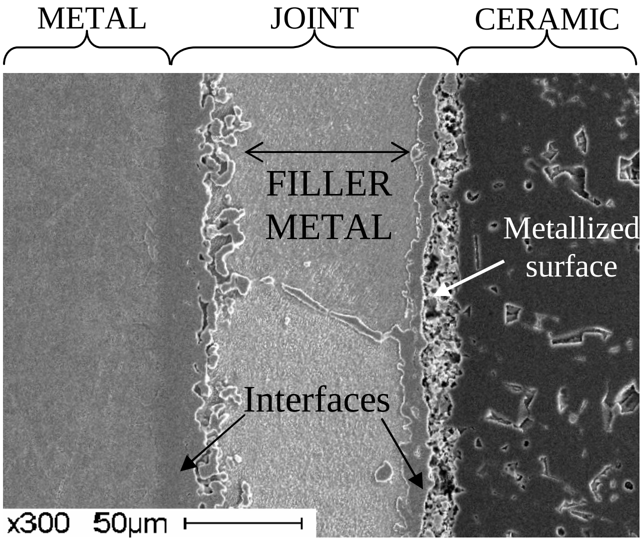

Figure 2. Microstructure of the ceramic to metal brazed assembly

Such ceramic metal brazed assemblies can fail by three different mechanisms: a) ceramic cracking in the direction normal to the ceramic-filler metal interface; b) ceramic metal interface decohesion; c) excessive plastic strain and void growth within the metallic materials (filler metal or metallic component).

Determination of the thermo-mechanical behaviour of the different constituents

The materials (ceramic, metal and filler metal) considered in this study exhibit different thermo-mechanical behaviour. It is important to define precisely such response in order to estimate the residual stresses induced by the brazing process and the tensile strength of the ceramic metal assembly.

Ceramic. The ceramic material (alumina with purity of 97%) is known to be linear elastic and its properties do not depend on temperature for the temperature range of the brazing process (20°C to 850°C). Elastic parameters have been identified through ultrasonic tests at room temperature (Table 1). Besides, alumina is a brittle material which has different strength in tension and compression. Tensile tests and compression tests have provided the corresponding strengths of this material: respectively 175 MPa in tension, and 1750 MPa in compression. Finally, the Coefficient of Thermal Expansion (CTE) according to temperature has been identified through dilatation test (Table 1).

Metal and filler metal. The metal (stainless steel) and the filler metal (silver-copper eutectic alloy) exhibit elastoplastic behaviour depending on temperature: filler metal is perfectly elasto-plastic and metal exhibits linear hardening (Table 1). The evolution of the yield stress with temperature presented in Table 1 is given by the bibliography [8]. As before, dilatation tests have provided the coefficient of thermal expansion (CTE) according to temperature (Table 1). Note that the ductile damage within the metallic materials is neglected as the failure of the specimen occurs preferentially within the ceramic material.

Young modulus (GPa)							
T(°C)	20	100	200	300	400	500	600
A	330	330	330	330	330	330	330
FM	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	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 ($\times10^{-6}$ °C^{-1})							
T(°C)	20	100	200	300	400	500	600
A	-	6.2	7.4	7.8	8	8.1	8.2
FM	-	16.7	19.2	20.2	20.4	20.7	20.5
SS	-	18.4	20.3	20.9	21.3	21.4	21.7
Yield stress (MPa)							
T(°C)	20	100	200	300	400	500	600
FM	247	243	230	185	40	15	8
SS	247	243	169	148	136	133	125
Tensile strength (MPa)							
SS	973	774	667	635	633	589	517
Tensile failure strain (%)							
SS	48	44	38	34	35	34	34

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

Tensile test

Test method. The tensile test method of ceramic metal seals is based on the standard test method for tension and vacuum testing of metallized ceramic seals (ASTM F 19-64) [9]. In this paper, this test method is used to determine tensile strengths of ceramic metal specimens. The specimen is composed of two identical washers of filler metal (or braze alloy) which join a metal washer located at the centre of the specimen with two identical ceramic components on each side. The geometrical dimensions of the ceramic component are detailed in Figure 3 (the metal washer thickness is equal to 0.3 mm and the filler metal washer thickness is equal to 0.06 mm).

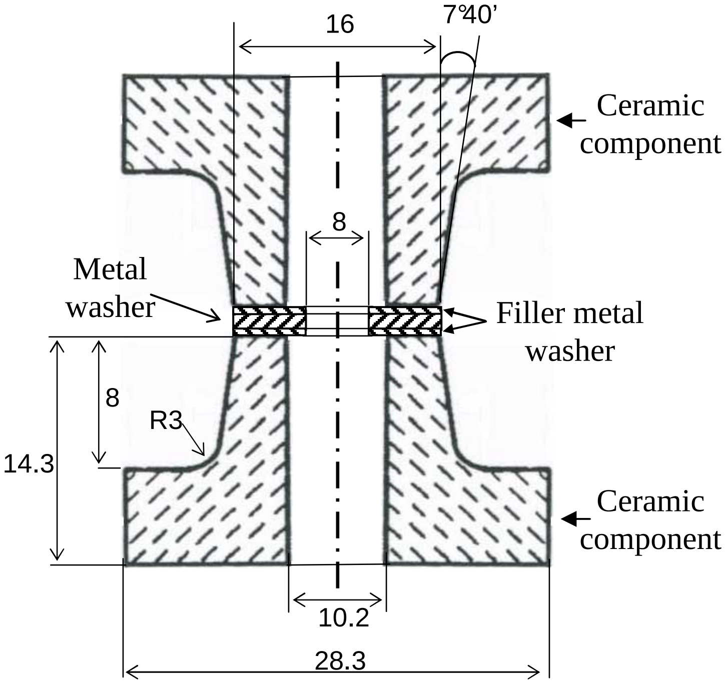

Figure 3. Tensile specimen geometry of ceramic metal seal (distances in mm)

The gripping device used to apply the load is presented on Figure 4. Such design allows a self aligning of the axis of the test specimen with the centreline of the test machine heads. The results dispersion for the identification of the tensile strength can then be significantly reduced.

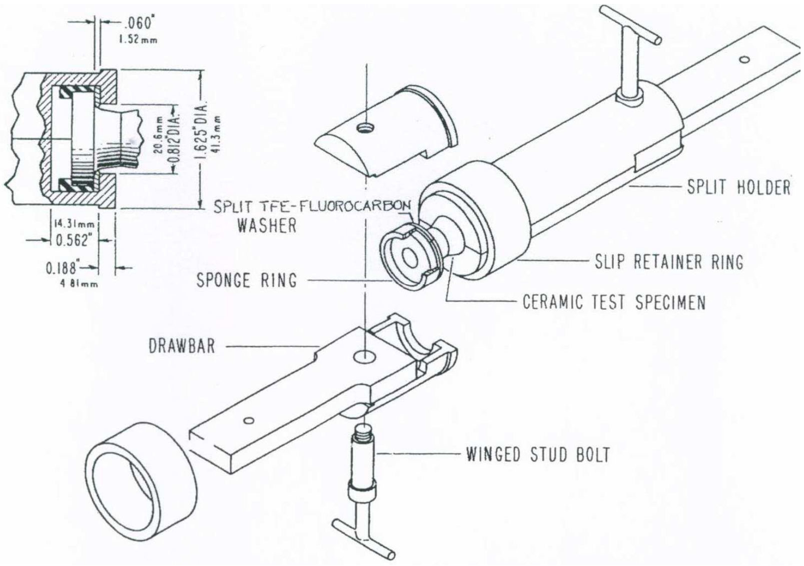

Figure 4. Self aligning grip for tension test [9]

Experimental results. Five specimens have been prepared and tested for this study. For each sample, Figure 5 shows the evolution of the load on the specimen according to the applied displacement of the grip. At the beginning of the test, we note a low non linear increase of the load, which corresponds to the aligning of the grip. Then, the response increases linearly up to the brittle failure of the sample which occurs within the ceramic material near the bond interface. Although the linear coefficient is quite the same for each specimen, the applied load that leads to the failure is quite different between the five samples (9.5 kN to 12 kN). The average of these five values is equal to 10.7 kN with a standard deviation of 1 kN. Note that the variability of the alumina tensile strength could explain such deviation of the results.

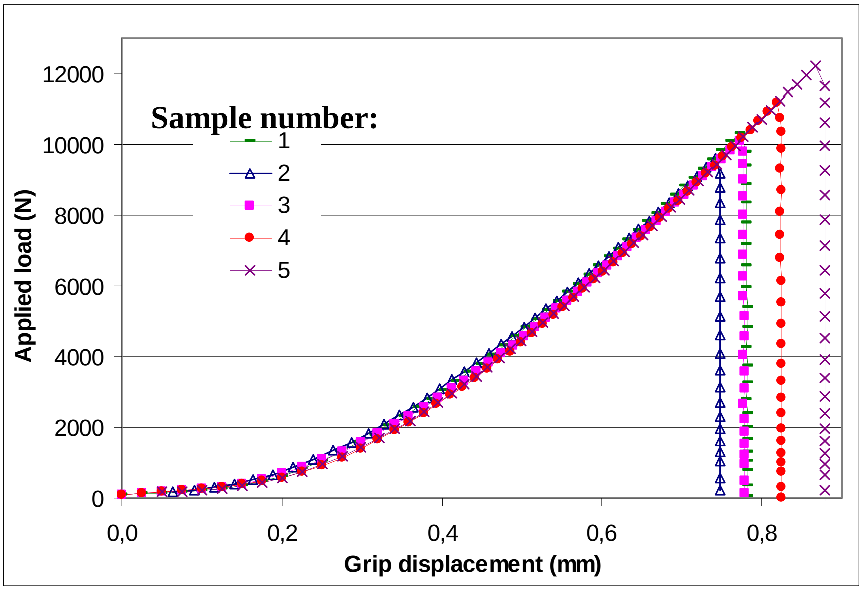

Figure 5. Tensile tests on ceramic metal assemblies.

Numerical model

Numerical simulations have been performed with the finite element ABAQUS code in accordance with the standard specimen geometry (Fig.3) and the processes involved. The numerical simulation is composed of two steps:

1. First, the cooling phase of the brazing process which provides the induced residual stresses in the materials,
2. In a second step, the tensile test itself which gives the tensile strength of the ceramic metal assembly.

For both stages, the following assumptions have been taken :

- the structure is 2D axisymmetric and symmetric with the median plane;
- the mesh of the assembly is constituted with 8-nodes quadratic axisymmetric quadrilateral elements. The element size is lowest near the interfaces and the free side surface because the residual stresses are essentially localised in theses zones and the failure occurs near theses zones during the tensile test (Fig. 6). A converging study on maximum principal stresses has fixed the nodes number at 5210 in our case to estimate residual stresses after brazing process and also stresses during the tensile test with a good precision;
- the interfaces between the filler metal and the base materials (ceramic and stainless steel) are supposed to be perfect.

Concerning the brazing process model:

- 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 with the uniform cooling hypothesis: the temperature of all the nodes is assimilate to the furnace temperature according to time.

Finally, for the tensile test simulation:

- the grip, made of hard steel, has been introduced in the finite element model (Fig. 6-b) : a linear elastic behaviour has been considered for this material (Young modulus 200000 MPa, Poisson ratio 0.3) and the contact between the grip and the specimen is simulated with a frictionless model;
- two initial stress states have been considered :
  1. first, free state of stress : the stresses equal to zero in all the specimen,
  2. then, pre-stressed state : the stresses are the residual stresses given by the previous simulation stage of the brazing process;
- a negative vertical displacement is applied on the lower surface of the grip (Fig. 6-b);
- the Rankine criterion is used to detect the crack initiation within the ceramic component : a crack is supposed to be initiated when the maximum principal tensile stress exceeds the tensile strength of the alumina.

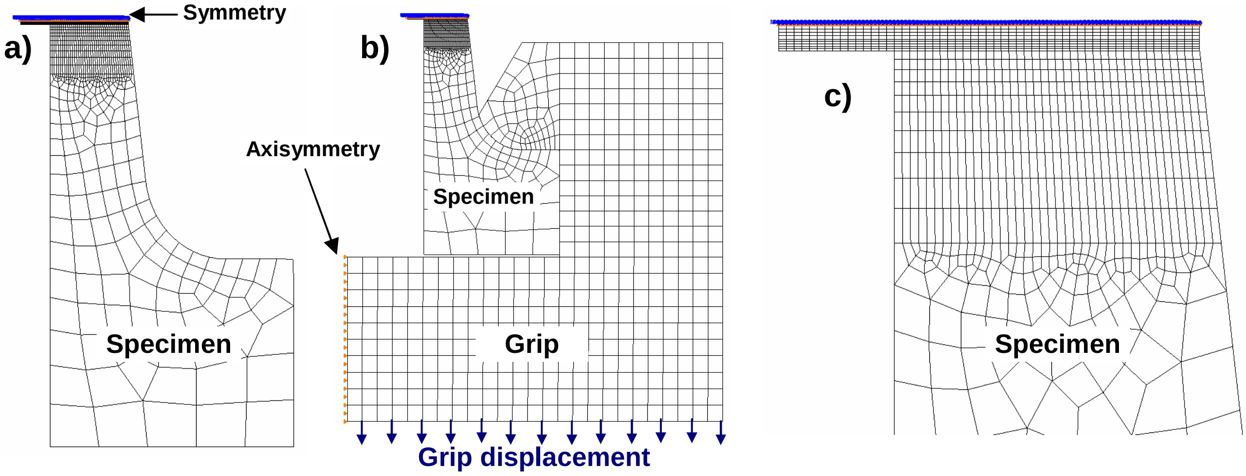

Figure 6. Mesh of the specimen: a) brazing process – b) tensile test – c) detail of the link zone

Numerical results. We have studied the stresses distribution at the end of the brazing process and the crack detection by the Rankine criterion during the tensile test.

For the brazing process model:

- Residual strains within the metallic materials are smaller than the failure strain limit. So the metallic materials are not damaged after the brazing process;
- The figure 7-a) gives the evolution of the maximum value within the ceramic part of the maximum principal stress according to the furnace temperature. The residual stresses are quite small within the assembly at high temperature because they are limited to the low yield stress value of the filler metal and associated to low strains values in metal and ceramic. The filler metal yield stress given by Levy [8] increases faster for the range of low temperature and then induces bigger stresses.
- Concerning the ceramic material, the maximum value of the maximum principal stress which controls the crack initiation (Rankine criterion) is located on the radial free edge of the specimen under the ceramic filler metal interface (Fig.7-b). This value is equal to 85 MPa after brazing which represents the half value of the ceramic strength. If ceramic is not damaged at the end of the cooling process, residual stresses induced are yet not negligible.

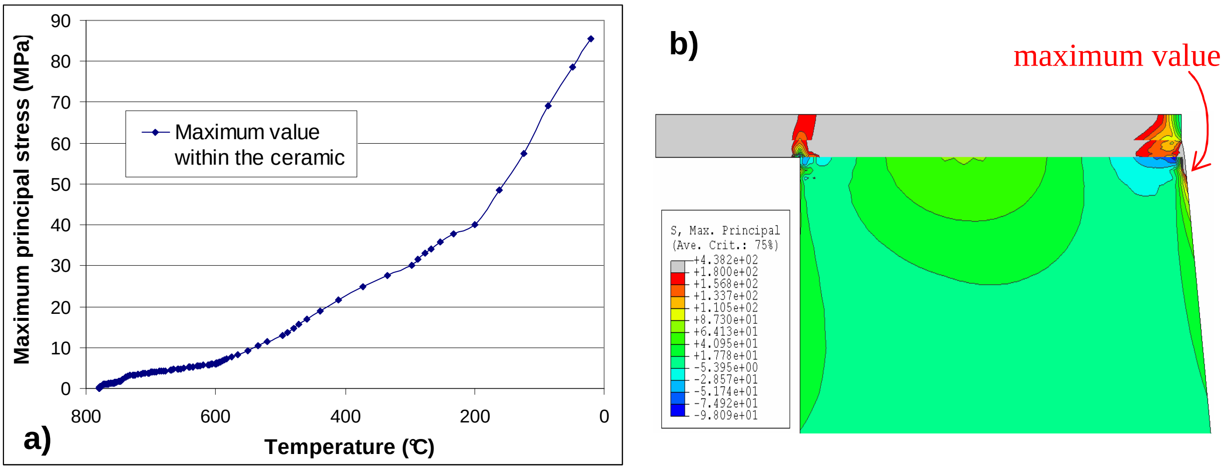

Figure 7. Maximum principal stress a) Evolution of the maximum value during the brazing process – b) final distribution within the specimen

For the tensile test, we have studied the evolution of the load on the specimen according to the stress evolution for the two initial stress states described before (Fig.8):

- For the free state of stress, the model shows that the failure load corresponding to the initiation of a crack within the ceramic part is around 20 kN;
- If the residual stresses are taken into account, this value comes to 10.5 kN, which is very close to the experimental results (mean value of 10.7 kN). This result is consistent with the fact that the residual effects reduce the amplitude of stress that can be supported by the ceramic. Consequently, it is essential to account for the residual stresses in order to estimate precisely the strength of the ceramic metal brazed assemblies.

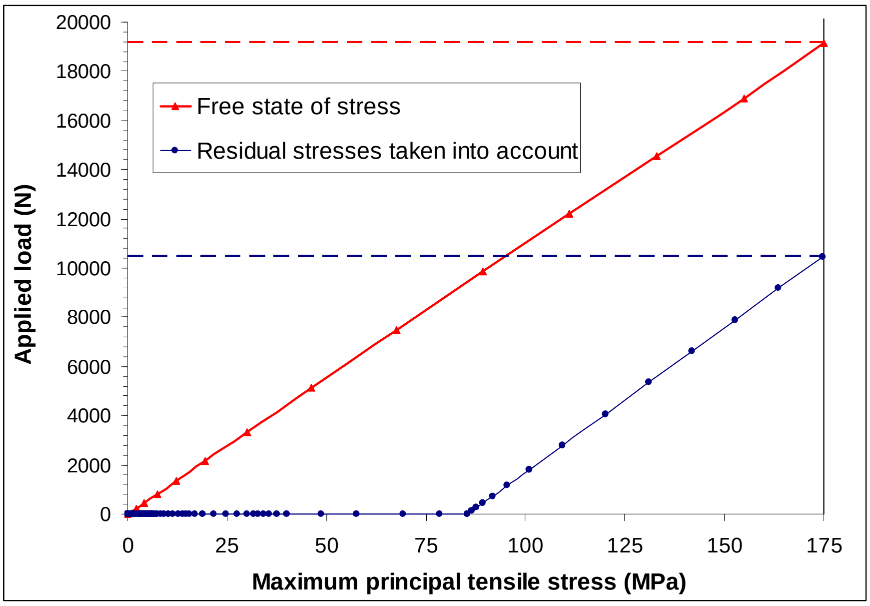

Figure 8. Tensile loading on the specimen according to the maximum principal stress evolution within the ceramic part

Conclusion.

The brazing process model presented in this paper allows an estimation of the residual stresses within ceramic metal assemblies induced by the cooling phase. The introduction of such stresses in the tensile test model leads to a better estimation of the tensile strength of standard specimens, consistent with experimental results. In view of the design of joints in engineering structures, the numerical model developed in this work represents then an essential tool to study the mechanical behaviour and the reliability of ceramic metal brazed assemblies. Note finally that it may be interesting to complete this work by simulating the damage growth within the ceramic material and to compare to the crack pattern generated during experimental tests.

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