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Study and mechanical characterization of high temperature power electronic packaging

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Abstract:

The increase of electric power demand for embedded systems requires more efficient power electronics modules (power converters, rectifiers ...). A solution to reach this goal relates to the use of high gap electronic chips as diamond-based components that allow high voltage and current density. The induced module design obviously sorely increases the maximum thermal and thermomechanical stresses in the packaged modules. In this work, we carry out experimental and numerical investigations of two types of high temperature silver connections elaborated at low temperatures by means diffusion heat treatment and by sintering. Mechanical behaviour of the junction is characterized by shear tests. At last, numerical simulations are used to simulate process and services thermal cycles and to assess stresses level at several stages of the assembly service life. All testing and simulation works allow validating the accuracy of the two kinds of connections and demonstrating their interest.

Keywords: thermomechanical, thermal cycling, FEM, electronic packaging, high temperature, sintering, TLPB.

1 Introduction

The increase of electric power demand for embedded systems requires more efficient power electronics modules (power converters, rectifiers ...). A solution to reach this goal relates to the use of high gap electronic chips as GaN [1, 2] or diamond based components [3, 4] that allow high voltage and current density. The induced module design obviously sorely increases the maximum thermal and thermomechanical stresses in the packaged modules and also the maximum allowable junction temperature. The major consequence of this choice is the need to work over a wide range of temperature from -50°C to 300°C. The high operating temperature involves the use of brazing alloys with high melting point to minimize the viscoplastic and damage phenomena of the junctions. However, a high elaboration temperature involves, after cooling, a high level of initial stress in the assembly [4], to the detriment of its mechanical strength. To reduce these effects, a solution would be to use low temperature junction elaborated by means transient liquid phase bonding (TLPB) or sintering in order to obtain a junction with high melting point temperature. Thus, as the elaboration temperature defines the unstressed state, these processes allow having a lower initial stress state and a better well-balanced stress state during the thermal cycling.

In this work, we propose to study and characterize two types of high temperature connections elaborated at low temperatures i.e. Ag-In based connection obtained by diffusion heat treatment and silver nanoparticles obtained by sintering process. For Ag-In assembly, the bonding process is realized at 400°C, while for the silver nanoparticles sintering, the elaboration temperature is 275°C. The first part of the study, deal with the connection process of copper inserts using the two kinds of process. In the second part, the mechanical behaviour of the junction is characterized by shear tests on a dedicated device. In the last part, numerical simulations are used to investigate the thermomechanical behaviour of a diamond-based assembly. We study the level of initial stresses in the joints and the resistance to thermal cycling as a function of the elaboration mode of the assemblies.

2 Experimental procedure

2.1 Description of the assembling process

In the experimental study, copper inserts of dimensions $3 \times 3 \times 2$ mm are bonded on copper substrates of dimensions $30 \times 20 \times 2$ mm. The assembling tested processes were TLPB Ag-In or silver nanoparticles sintering. The diamond dies will replace the copper inserts for the power electronic investigations once the efficiency of the connection mode approved.

2.1.1 TLPB Ag-In

For the TLPB Ag-In, the Cu substrate is electroplated with silver and indium layer with a respectively thickness of $50 \mu\text{m}$ and $10 \mu\text{m}$. The Cu inserts are electroplated with a silver layer of $40 \mu\text{m}$ thickness (figure 1.a). Afterward, the electroplated parts are cleaned in an ethanol bath for organic contaminations removal. The two parts are then held together with a static pressure of 6 MPa to ensure an intimate contact. The assembly is then mounted on the heating platform. The joint is achieved at 205°C bonding temperature with dwell time of 10 minutes (figure 1.b). After air-cooling to room temperature, the bonded samples are annealed at 400°C to get a very rich silver joint (90% of Ag and 10% of In) [5]. According to the In-Ag phase diagram [6], the expected melting temperature of Ag-In connection obtained is as high as 850°C .

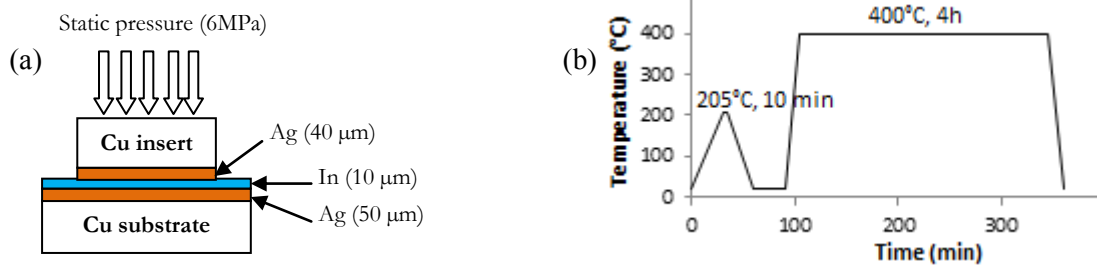


FIG. 1 - Bonding process of the TLPB Ag-In: (a) multilayer structure, (b) temperature profile.

2.1.2 Silver nanoparticles sintering

Nanosilver paste used in this study was provided by NBE Tech LLC [7]. It is included 71 to 91 wt.% of silver nanoparticles and organic components such as binder, surfactant and thinner.

After cleaning the surfaces (polishing and contaminations layers removal), a $40 \mu\text{m}$ Ag coating is electroplated on the two Cu parts. The nano Ag paste is deposited on the Cu substrate. The two parts are assembled together as shown in figure 2.a. The samples were put onto the heating platform and heated following the temperature profile shown in figure 2.b. The organic components in the paste were volatilized and burnt out before the densification occurred at the stage of 275°C . After sintering, the system is cooled down naturally at room temperature. The overall cycle time duration is approximately 2 hours. The melting point of the nano Ag sintering connection is as high as 962°C .

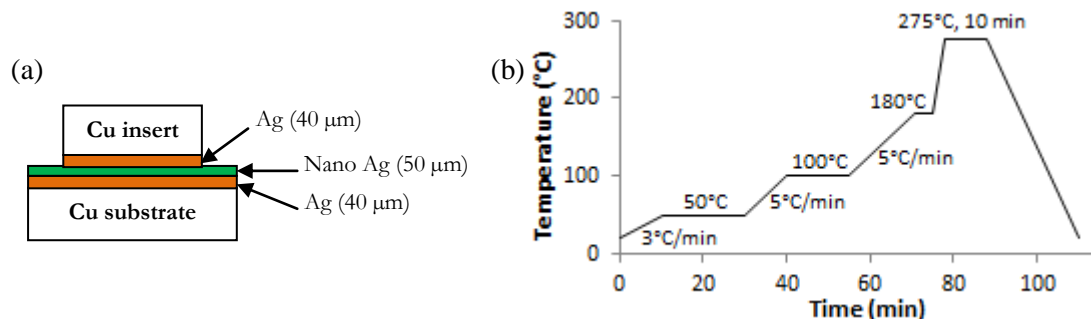


FIG. 2 - Bonding process of the nano Ag sintering: (a) multilayer structure, (b) sintering temperature profile.

2.2 Experimental results analysis

Shear test is a very common way to evaluate the mechanical properties of microelectronic joint and die attach. To determine the strength of the TLPB Ag-In and nano Ag joints, simple shear test at room

temperature were performed on 6 specimens for each kind of assembly using an INSTRON apparatus dedicated to perform shear tests on electronic devices. The testing configuration is shown in figure 3.a.

Figure 3.b and 3.c present the results from simple shear test for the two joints. All the results exhibit a good repeatability. In the case of TLPB Ag-In joint, the maximal applied load exceeds 570 N and the shear stress at failure varied from approximately 54 to 63 MPa. The displacement at failure reaches 0.7 mm. Mechanical behaviour of nanosilver joint is presented in figure 3.c. The maximal applied load does not exceed 280 N and the shear stress at failure varied from approximately 26 to 31 MPa. In this case, the junction fails at a maximum displacement of 0.47 mm.

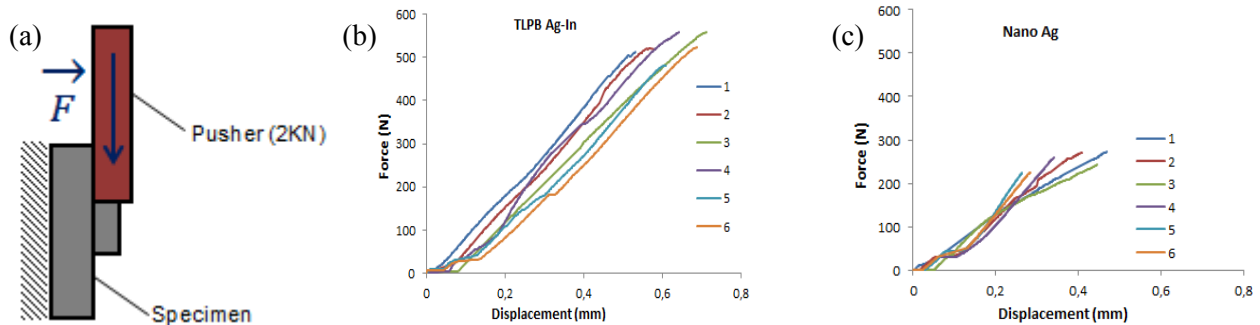


FIG. 3 - Shear test experiments at room temperature: (a) testing configuration, (b) results for Ag-In junctions, (c) results for nano Ag junctions.

There is a little amount of plastic deformation produced in the two joints layer. Higher load values are reached for the Ag-In which are twice higher than the silver nanoparticles junction ones. The interfacial behaviour of the junctions is quite interesting. However, the failure seems first to appear near the interfaces. To verify these assumptions, the failure zones were analysed using the scanning electron microscope. The failure zones are shown in figures 4 and 5 respectively for the Ag-In and nano Ag specimens. The EDX analysis of Ag-In specimen failure shows only the presence of Ag and In. The micrographs and EDX analyses of Ag-In broken specimen illustrate an homogenous and cohesive fracture in the joint near to the copper insert (figure 4). EDX spectra analyse of nano Ag specimen failure shows only silver (figure 5). The micrographs and spectra analyse of nano Ag sintered specimen illustrate a mixed mode of failure in the middle of the joint and between electroplating Ag of Cu insert and nano Ag joint.

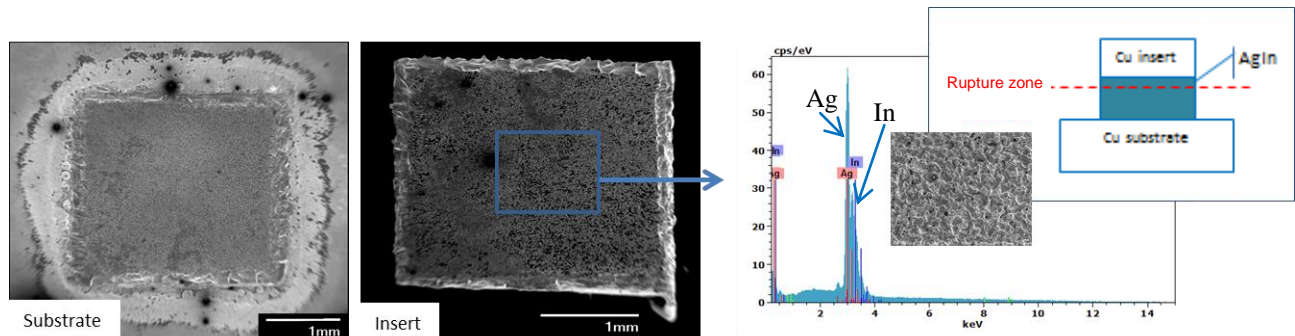


FIG. 4 – SEM Micrographs of Ag-In specimen failure and EDX analysis of the same zone.

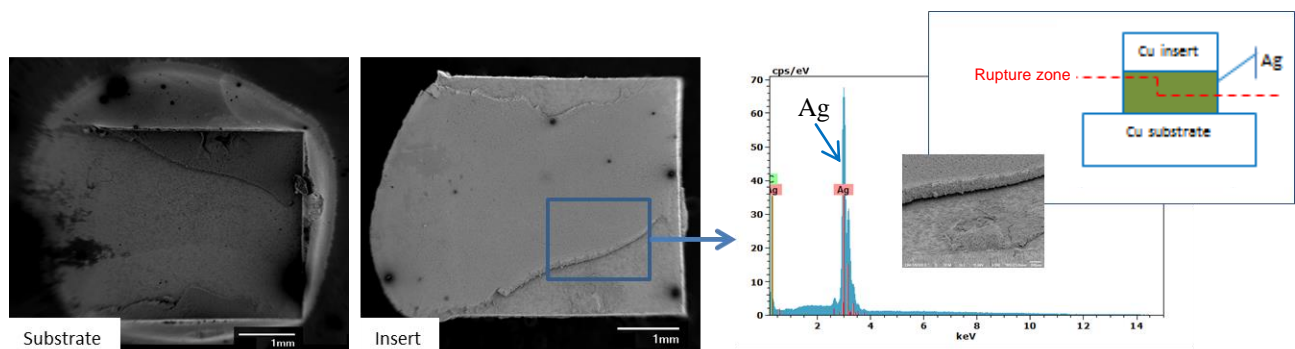


FIG. 5 - SEM Micrographs of nano Ag specimen failure and EDX analysis of the same zone.

3 Finite element evaluation of the junctions behaviour

The power electronic packaging is composed of a diamond die, of dimensions $3 \times 3 \times 0.5$ mm, and a copper metallized ceramic substrate Si_3N_4 which are bonded together with either TLPB Ag-In or silver nanoparticles sintering. The thickness of the Ag-In and nano Ag joints is about $100 \mu\text{m}$. To simulate the thermomechanical behaviour of die attachments, 2D FEM model was realized with Abaqus® software as shown in figure 6.a [3, 4]. Since the electronic assembly is symmetric, a half model is considered in these computations. All material properties adopted in the simulation are presented in Table 1.

Anand constitutive model is commonly used for high creeping materials and is used here to describe the viscoplasticity of the die attachments materials [8, 9]. Since there is no Ag-In viscoplastic model parameter in the literature, we have considered mechanical properties the same as those of pure Ag. Indeed, as we want to establish a comparison between the both processes it can be a legitimate to use the same viscoplastic behaviour model for both joints, even if indium ratio is not insignificant. The Anand model parameters [9, 8] are given in Table 2. The identification of these parameters was studied by Gang Chen et al. for the nanosilver based power packaging [10, 11]. The diamond die and Si_3N_4 ceramic substrate are taken as pure elastic materials. Copper metallization is considered to have elastoplastic mechanical behaviour.

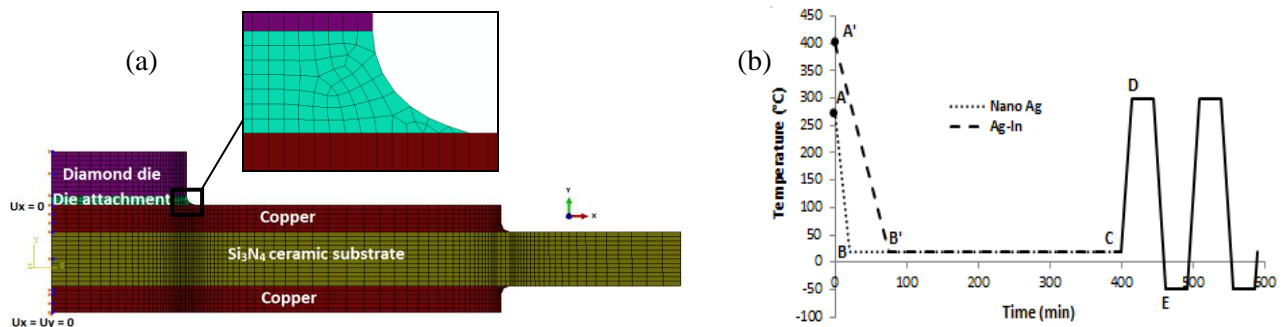


FIG. 6 - Modeling of 2D power electronics packaging: (a) simplified packaging architecture, (b) imposed temperature profile.

| | Elastic modulus (GPa) | Poisson's ratio | Thermal conductivity ($\text{W.m}^{-1}.\text{K}^{-1}$) | Mass density (Kg.m^{-3}) | Specific heat capacity ($\text{J.Kg}^{-1}.\text{K}^{-1}$) | Thermal expansion coefficient ($\mu\text{m.m}^{-1}.\text{K}^{-1}$) |
|-------------------------|-----------------------|-----------------|--|-------------------------------------|---|--|
| Diamond | 1000 | 0.22 | 1600 | 3500 | 640 | 2 |
| Ag-In | 76 | 0.37 | 419 | 9300 | 234 | 19.6 |
| Nano Ag | 10 | 0.37 | 240 | 8000 | 234 | 19.6 |
| Copper | 128 | 0.36 | 398 | 8850 | 380 | 17.3 |
| Si_3N_4 | 310 | 0.27 | 60 | 3290 | 800 | 3.3 |

Table 1 - Properties of materials used for the power packaging.

| A (s^{-1}) | Q/R (MPa) | M | n | ξ | \hat{s} (MPa) | h_0 (MPa) | s_0 (MPa) | α |
|-----------------------|-----------|--------|---------|-------|-----------------|-------------|-------------|----------|
| 9.81 | 5706.3 | 0.6572 | 0.00326 | 12 | 101.7 | 14600 | 2.93 | 1 |

Table 2 - Material parameters of Anand model for the TLPB Ag-In and the sintered nanosilver [10, 11].

The packaging is subjected to thermal cycling as presented in figure 6.b. The thermal cycle is decomposed into a reflow cycle included in the manufacturing process and a thermal temperature cycling imposed for a temperature range of -50°C to 300°C with a heating/cooling rate of $20^\circ\text{C}/\text{min}$. A dwell time of 30 min is considered at -50°C and 300°C . The imposed heating/cooling profile is composed of 10 cycles. During the elaboration process and thermal cycling, the mismatch of thermal expansion coefficients (CTE) between the die and the substrate caused stress and viscoplastic strain in the bonding layer [4, 10]. After the simulations and in order to observe the CTE mismatch effects on the thermomechanical behaviour of the junction, the stress and the strain values are extracted on the bonding layer for comparison purposes between the two die attachments.

Figure 7 presents the Von Mises stress distribution after manufacturing process on the two joint layers. For both the Ag-In and nano Ag joints, distributions of the stress are similar. The maximum stress value is located near the interface with the die. After elaboration process (point B and B') figure 7.a, Ag-In is more

solicited than nano Ag joint. The Von Mises stress reaches a value of 31 MPa and 27 MPa respectively for Ag-In and nano Ag. However, after relaxation (point C) as shown in figure 7.b, the nano Ag joint is more solicited than the Ag-In joint. For both the two joints, the effective stress decreases and reaches 2.5 and 4.9 MPa respectively for Ag-In and nano Ag. We preview, that after relaxation, the stress of nano Ag is twice more higher than Ag-In.

Figure 8 shows the stress distribution on the Ag-In and nano Ag junctions in the first thermal cycle at high and low temperature (respectively points D and E). For both the Ag-In and nano Ag, stress is higher in the cooling step near the interface between die and joint layer. This is obvious because diamond has the highest rigidity among the whole assembly materials. The solder is more solicited along the die side. The effective stress reaches a value of 75 and 60 MPa respectively for Ag-In and nano Ag. In the step of heating (point D), the stress is very low and doesn't exceed 1 MPa for the two joints. It looks that Ag-In is more solicited than nano Ag joint at high and low temperature.

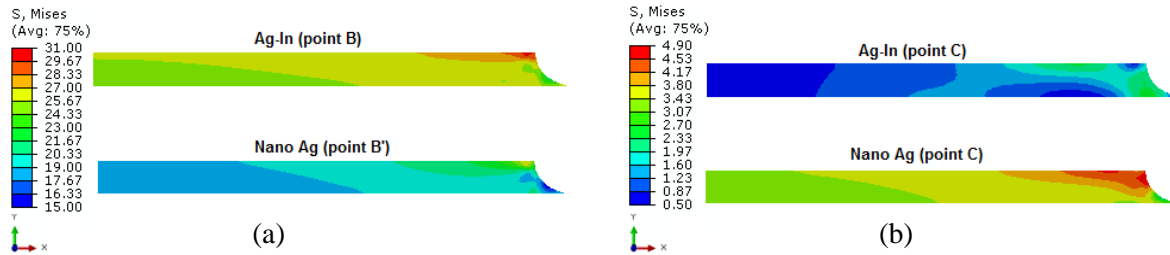


FIG. 7 - Stress distribution in the joint layers after manufacturing process of the two configurations: (a) after elaboration process, (b) after relaxation (points B, B' and C are shown figure 6.b).

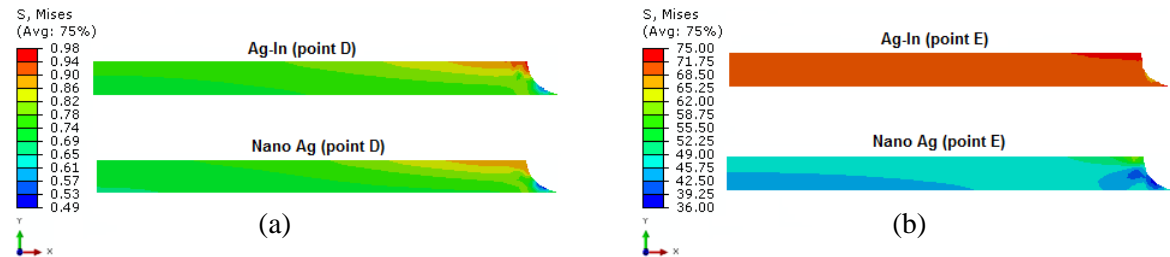


FIG. 8 - Stress distribution in the joint layers after thermal cycling of the two configurations: (a) at high temperature (point D), (b) at low temperature (point E) - (points D and E are shown figure 6.b).

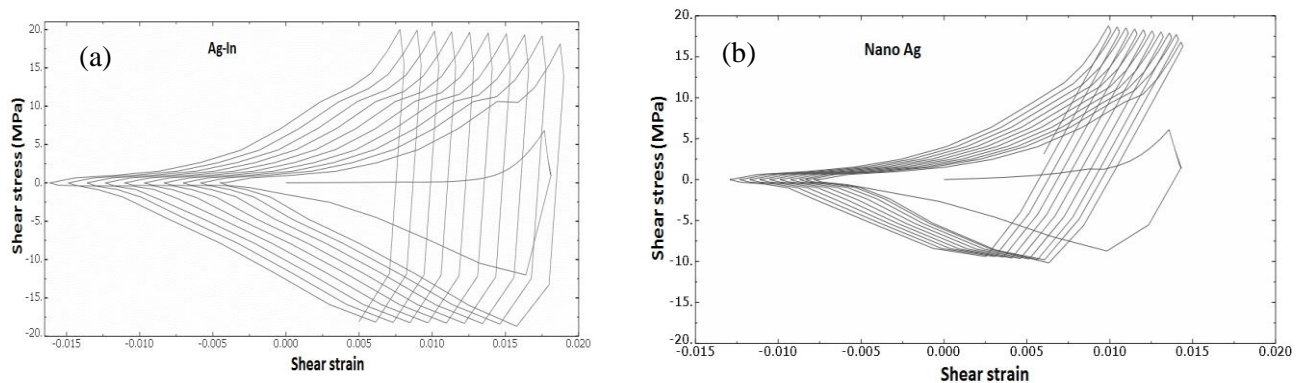


FIG. 9 - Shear stress versus shear strain of the two configurations: (a) Ag-In joint, (b) nano Ag joint.

The results in figure 9 are extracted at an integration point in a same element for the two joints. For Ag-In (figure 9.a) and nano Ag (figure 9.b) joint, there is increasing of shear stress respectively from 7 to 20 MPa and from 6 to 18 MPa. The stress responses stabilize in the 5th cycle for the Ag-In joint and in the 8th cycle for the nano Ag joint. For Ag-In joint, the total shear strain reaches 1.9% at the first cycle of loading then it decreases to 0.8% at the end of the loading. We can observe the same results for the nano Ag joint (figure 9.b), the total shear strain reaches 1.45% at the first loading cycle then it decreases progressively to 1% at the end of loading. Viscoplastic strain energy density is extracted in an integration point of the layer where Von Mises stress is maximal. As observed in figure 10, that the Ag-In joint viscoplastic strain energy density is higher than those of the nano Ag joint. Time to failure will be assessed basing on this evaluated strain energy

density. The value of the accumulation per cycle is $1.09 \cdot 10^6 \text{ J/m}^3$ and $0.54 \cdot 10^6 \text{ J/m}^3$ within the last cycle respectively for Ag-In and nano Ag joints. These results illustrate that the Ag-In joint has a mechanical strength more important than the nano Ag joint and these assumption was verified by the obtained experimental shear test.

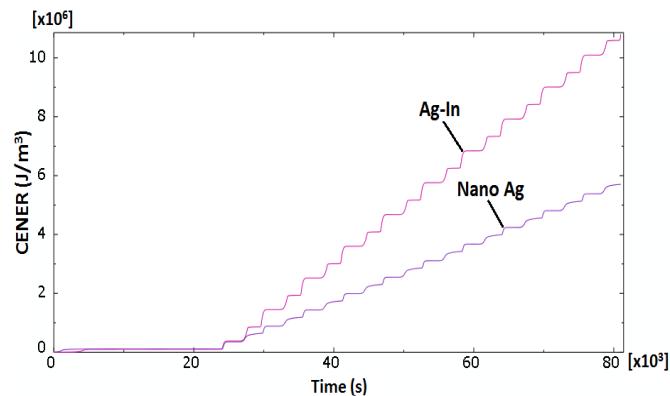


FIG. 10 - Viscoplastic strain energy density versus time of Ag-In and nano Ag joints.

Conclusion

Two diamond-based packaging configurations designed for high temperature and high power packaging applications are studied. The packaging is composed with two types of high temperature die attachments: TLPB Ag-In and silver nanoparticles sintering. The experimental data allowed approving the steps of manufacturing process and the mechanical behaviour of the two joints. High quality joints are achieved at 400°C and 275°C bonding temperature respectively for TLPB Ag-In and nano Ag sintering. The FEM of 2D power packaging architecture allowed evaluating the stress distribution in the two joint layers after manufacturing process and thermal cycling, shear stress versus shear strain and the viscoplastic strain energy density. The FEM permitted to demonstrate that nano Ag based packaging is less solicited after elaboration process and during the thermal cycling, but after relaxation this die attachment is more solicited than the Ag-In joint. Experimental and numerical results show that Ag-In has a higher strength compared with the nano Ag. Since we considered that mechanical properties for Ag-In as the same as those of Ag, the Ag-In based packaging can be promoted solution.

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