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Functionally Graded Materials:

prevision of properties and performances

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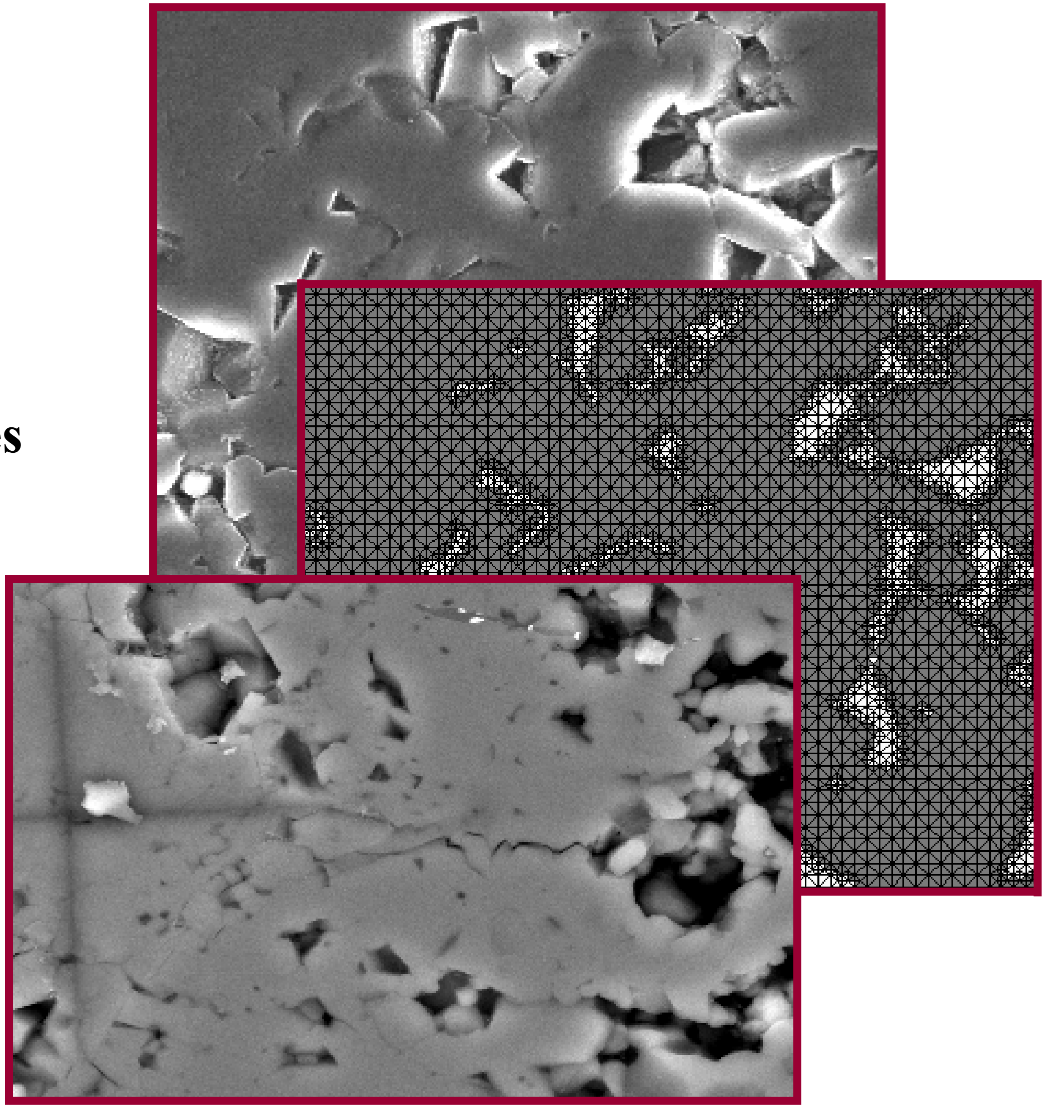
Presentation outline:

- Introduction – FGMs
- Materials
- Simulations:
  - Thermal residual stresses
  - Elastic modulus
  - Fracture propagation
- Conclusions



Outline

Introduction – Functionally Graded Materials (FGMs)

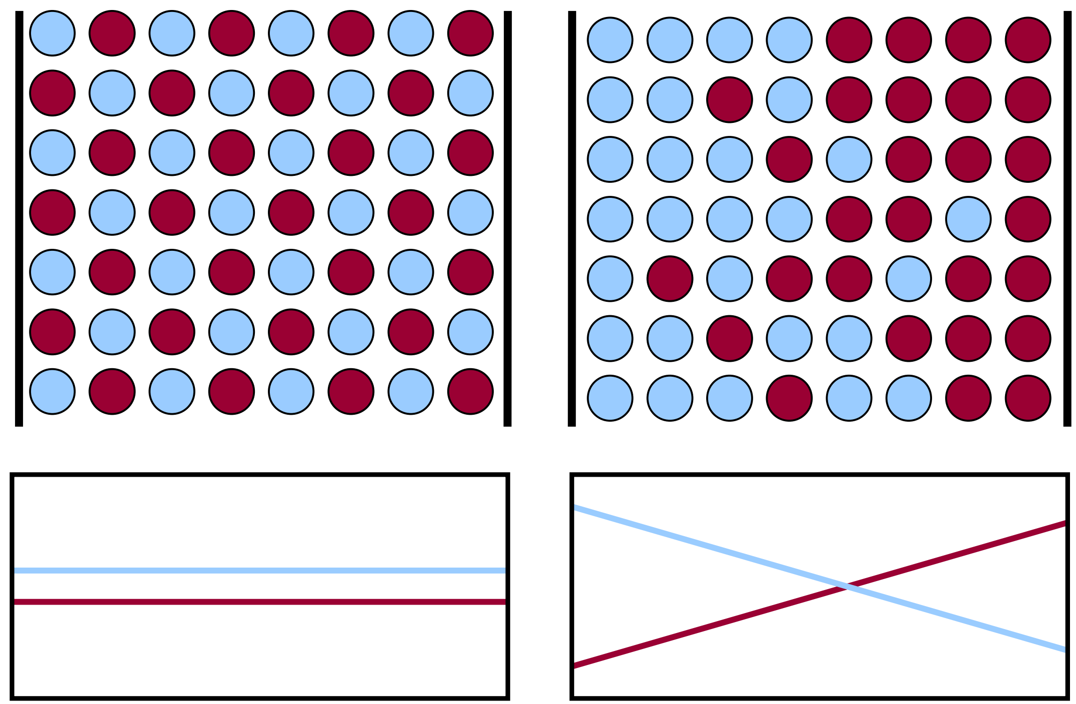
FGMs are innovative composite materials whose composition and microstructure vary in space following a predetermined law. The gradual change in composition and microstructure gives place to a gradient of properties and performances [1].

= constituent phase A

= constituent phase B

= property A*

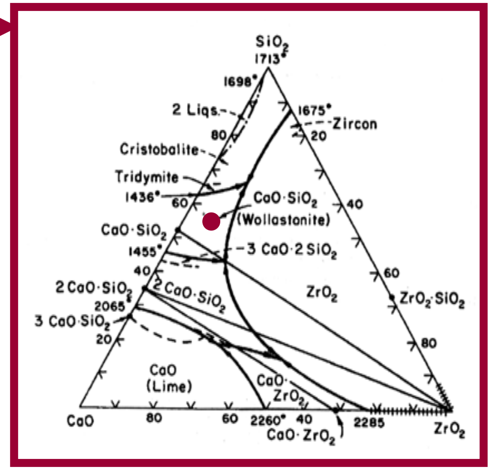
= property B*



Materials

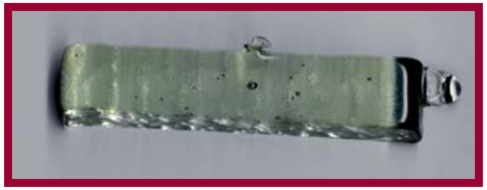
Constituent phases

The *glass* [2] belonged to the $CaO\text{-}ZrO_2\text{-}SiO_2$ system:



- Its composition did not contain Al_2O_3
- Its coefficient of thermal expansion was similar to the alumina one
- Its chemical, physical and mechanical properties were relatively good [2]:

Young's modulus	Poisson's coefficient	Coef. ther. expansion	Toughness
96.2 GPa	0.27	$8.6\ 10^{-6}\ K^{-1}$	$0.9\ MPa\ m^{1/2}$



The *alumina* was used in two different forms:

- **Polycrystalline sintered α-Al_2O_3 bulks were applied as substrates**
  - **Alumina bulks “A” (FN S.p.A. Nuove tecnologie e Servizi Avanzati, Bosco Marengo (AL), Italy) [2]**
  - **Alumina bulks “B” (Kéramo ceramiche tecniche, Tavernerio (CO), Italy) [3]**

	Young’s modulus	Poisson’s coefficient	Coef. ther. expansion	Toughness
Alumina A [2]	358.3 GPa	0.20	$8.2\ 10^{-6}\ K^{-1}$	$2.6\ MPa\ m^{1/2}$
Alumina B [3]	380 GPa	0.21	$8.3\ 10^{-6}\ K^{-1}$	$4.0\ MPa\ m^{1/2}$

- **An α-Al_2O_3 powder (Sulzer Metco 105SFP) was employed to obtain the plasma-sprayed functionally graded coatings [3]**

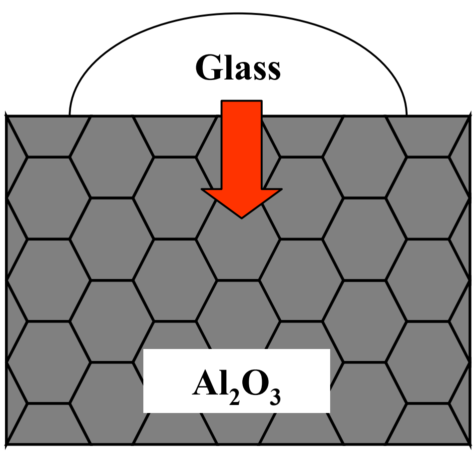
Materials

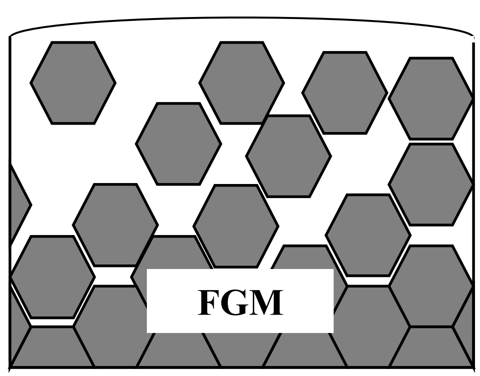
Fabrication techniques

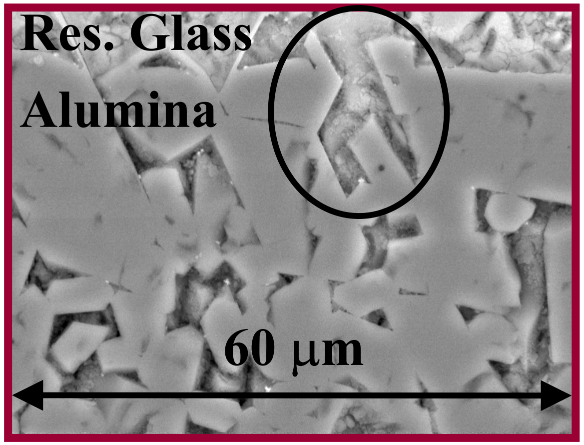
Two different methods were used:

- **Percolation** → **"Percolated FGM"**
- **Plasma spraying** → **From 0% to 100% glass** → **"FGM-PS1"**
  ↘ **From 20% to 100% glass** → **"FGM-PS2"**

***Percolation*: a thermal treatment induced the infiltration of the melted glass into the polycrystalline alumina substrate [2, 4].**

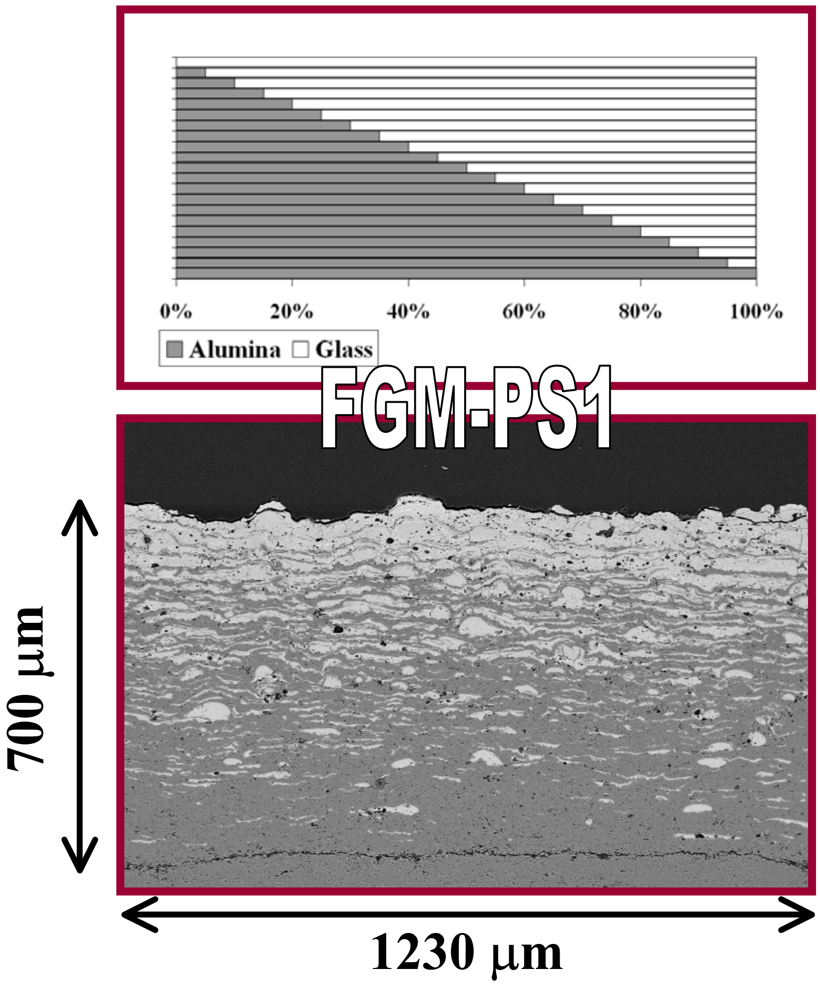


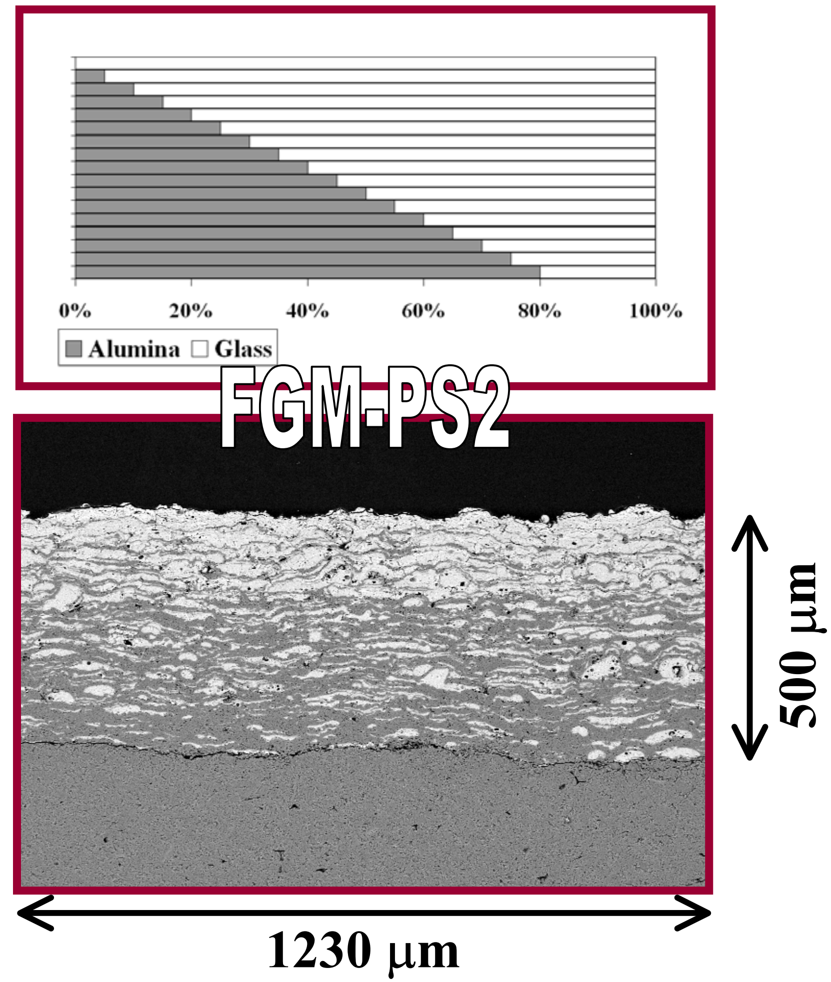




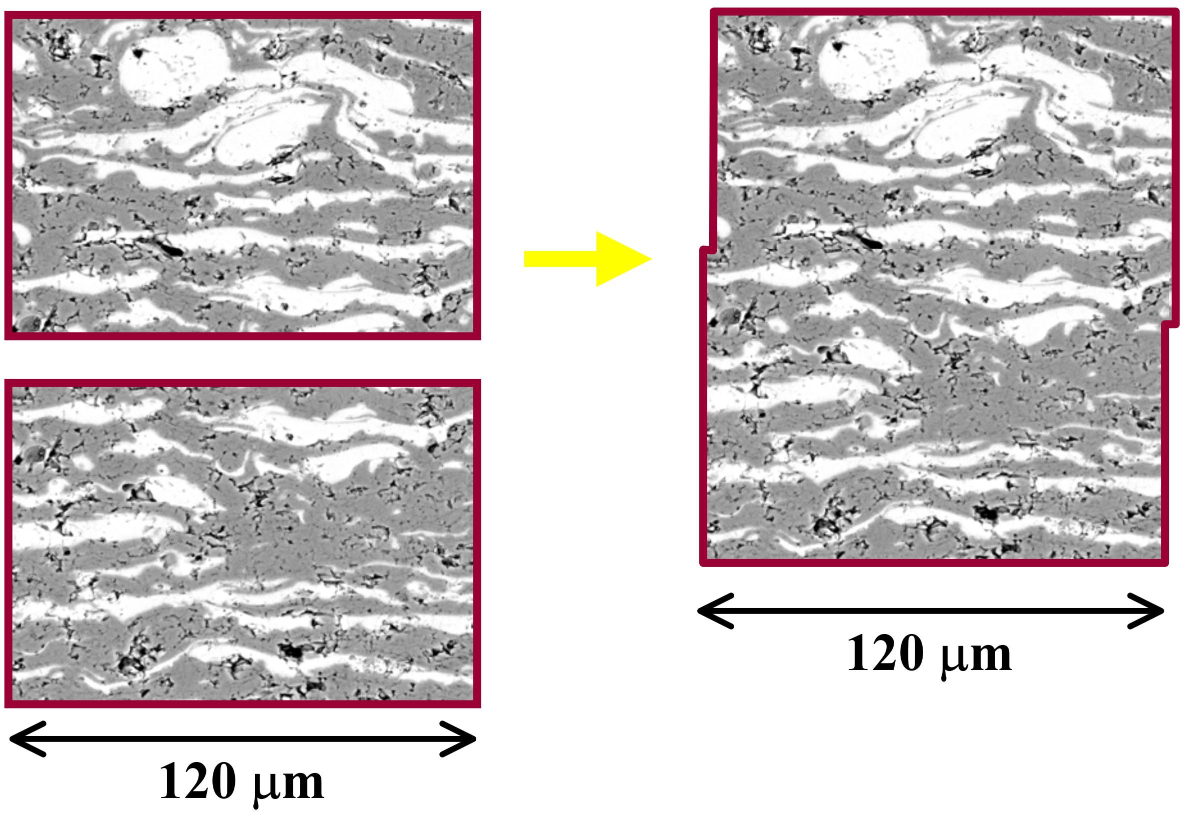
Materials

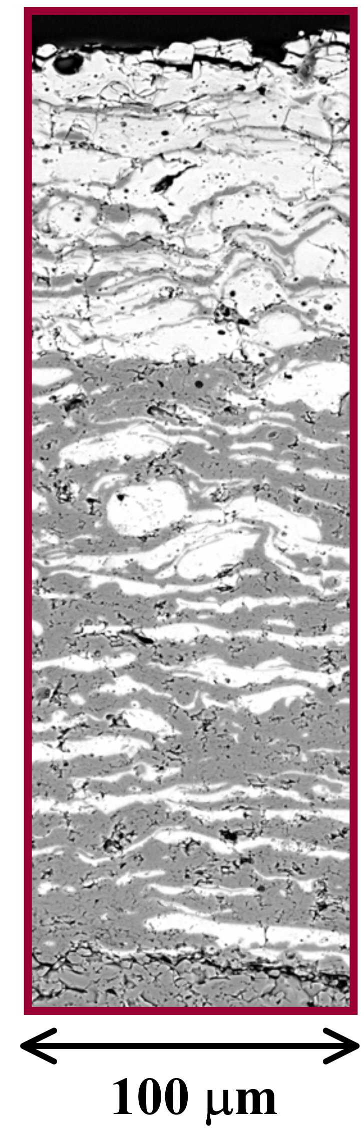
Plasma spraying: **multi-layered glass alumina functionally graded coatings were deposited on alumina substrates thus creating different profiles [3, 4]:**





Simulations



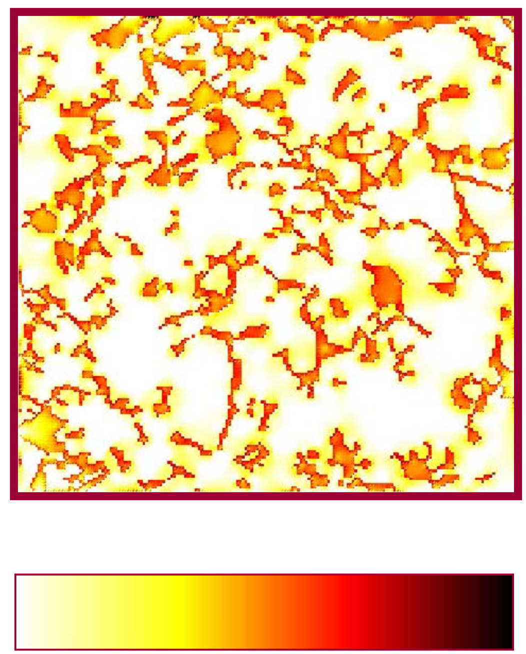


In order to account for the gradient, several SEM images were assembled and used to build the FEM grids.

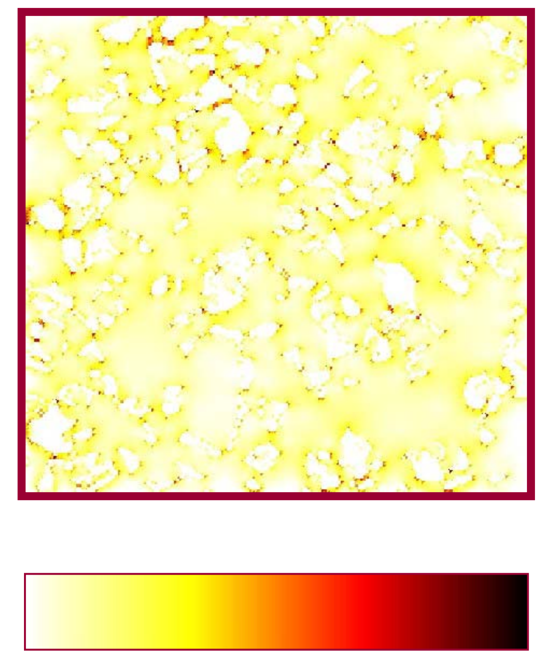
<u>Thermal residual stresses:</u> they were simulated and experimentally measured on samples obtained by percolation in alumina "A" substrates (maximum depth reached by the glass: 800 μm) [5, 6].

Microstructural detail

Tensile stress σ_{11}



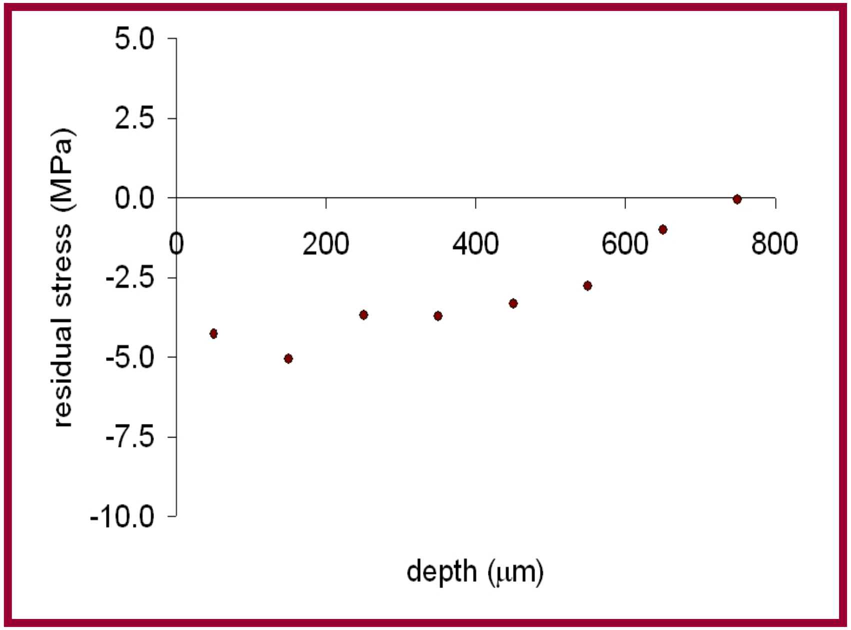
Compressive stress σ_{33}



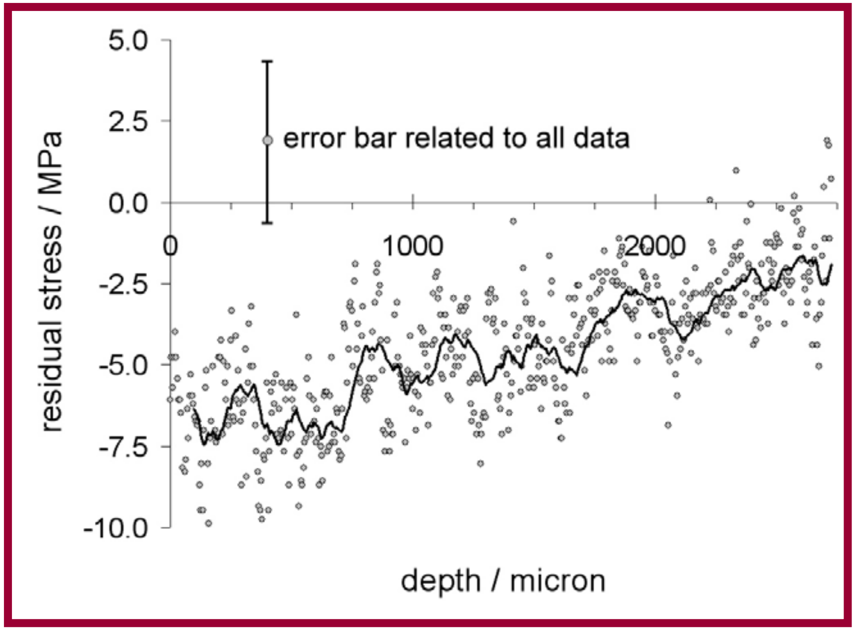
Simulations – Thermal residual stresses

The hydrostatic stress in the alumina was calculated as a function of depth along the glass infiltration direction. The simulated values were compared with the experimental ones, obtained by means of a piezo-spectroscopic technique [6].

Hydrostatic stress in alumina

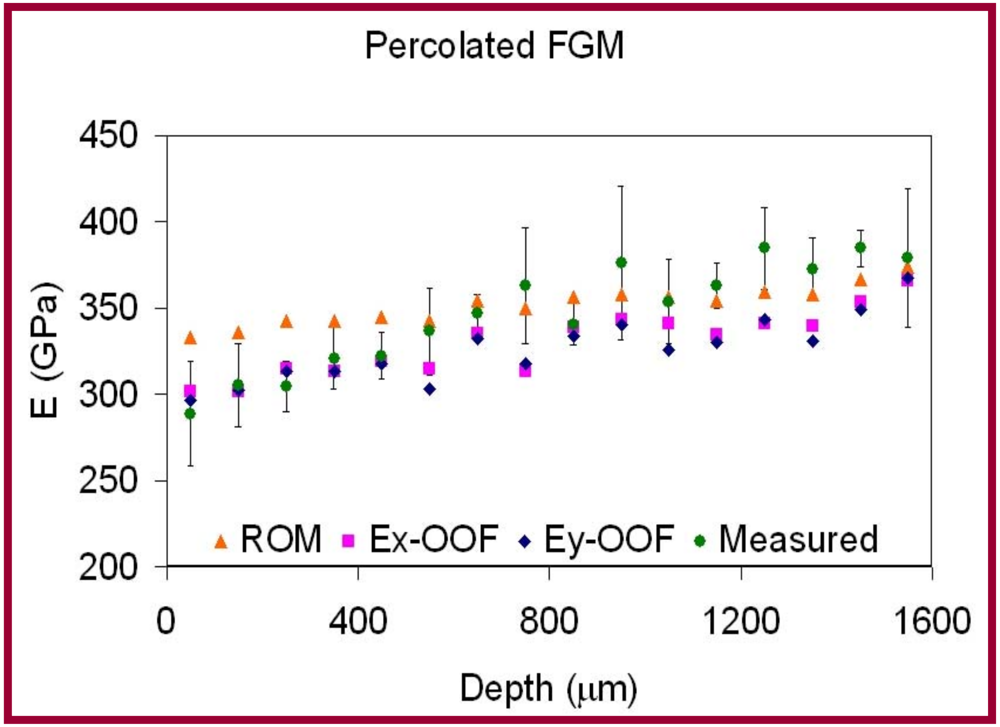


Simulation



Experimental

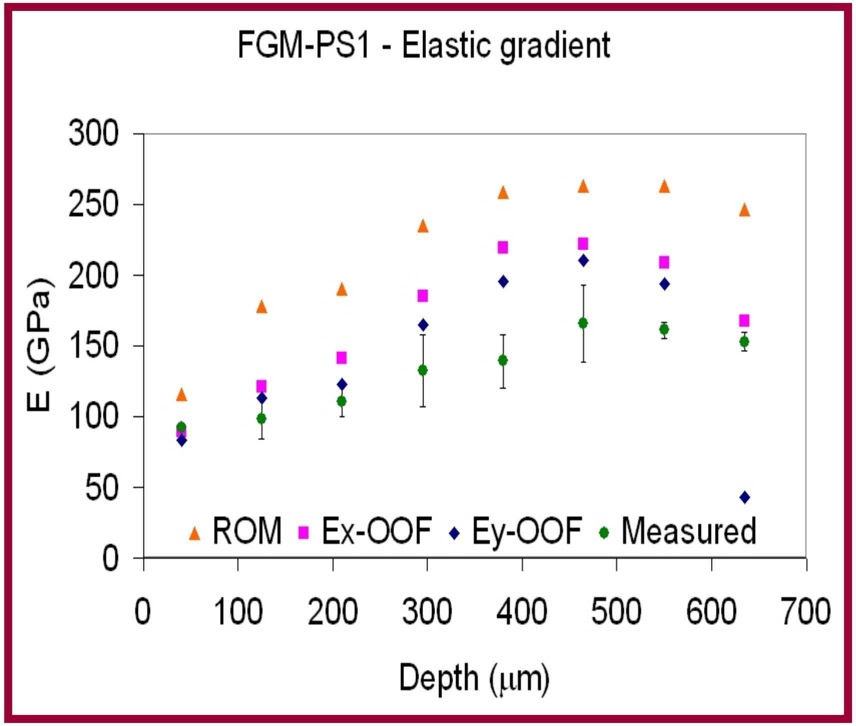
<u>Elastic properties:</u> OOF allowed to evaluate the elastic properties (Ex ⊥ gradient direction; Ey || gradient direction) as a function of depth. The so obtained values could be compared with the results of the Rule of Mixture and with the experimental data obtained via a depth-sensing Vickers micro-indentation test performed on the cross section [7].

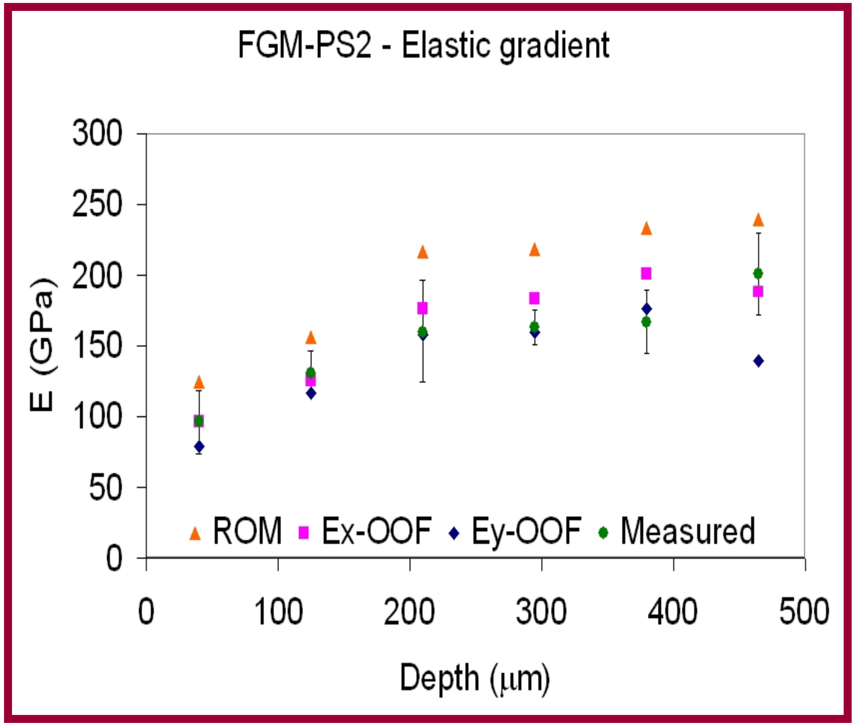


Sample obtained by means of percolation using alumina "B" substrates; maximum depth reached by the glass: 1600 μm.

Simulations – Elastic properties

In the plasma sprayed systems, the predicted values were slightly overestimated with respect to the experimental ones. The discrepancies were likely to be caused by microcracks and other defects which, due to their thinness, could be hardly seen in SEM images [7].



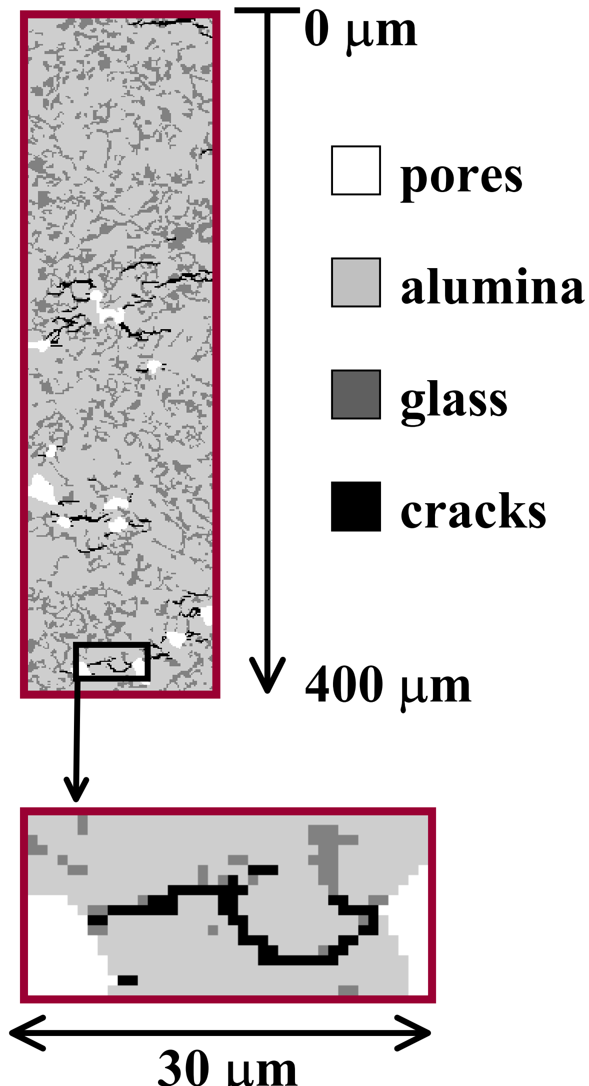


Simulations – Elastic properties

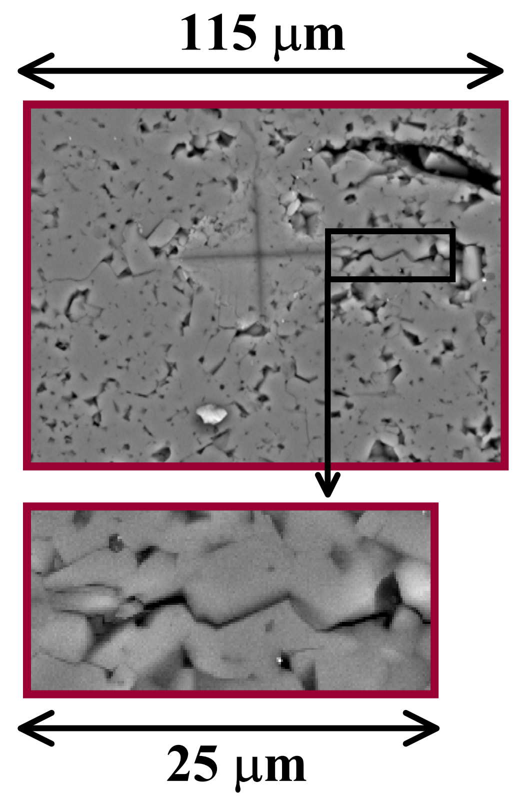
<u>Crack propagation</u>: in FGM specimens obtained via percolation, cracks mainly started from residual pores and then propagated through glass domains [8, 9].

The system failure was substantially governed by microstructural defects (pores) and glass spatial distribution [8, 9].

No delamination was predicted [8, 9].



Samples obtained by means of percolation using both alumina "A" [8] and "B" [9].



Simulations – Fracture propagation

In the plasma sprayed sample FGM-PS1, the weakest link – as far as the adhesion was concerned – was represented by the graded coating-substrate interface; the coating broke off from the substrate when the (simulated) applied strain was just 0.2% [9].

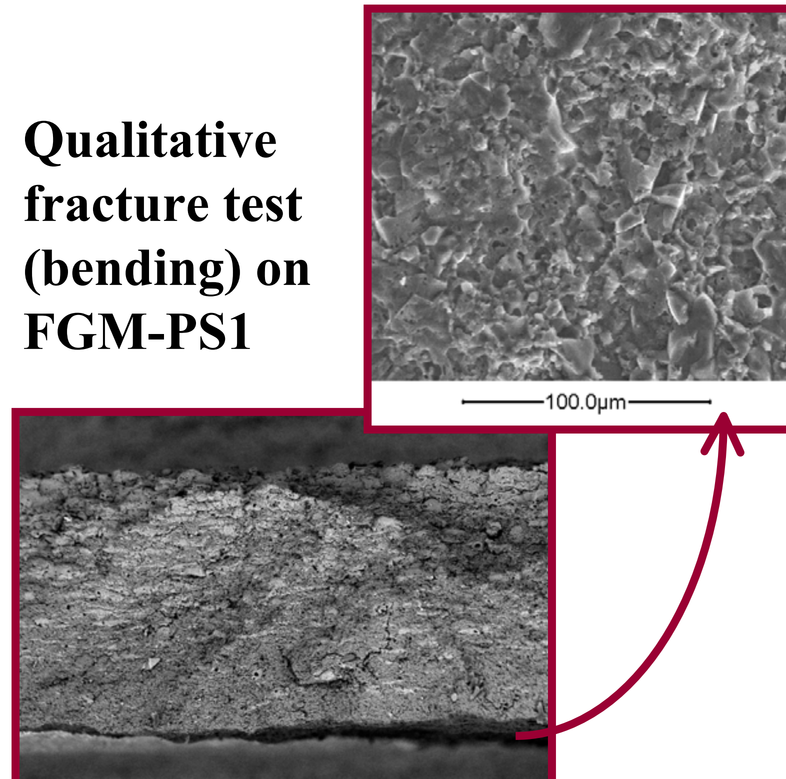
pores **alumina**

glass **cracks**

Qualitative fracture test (bending) on FGM-PS1

Coating-substrate interface

120 μm



1400 μm

Simulations – Fracture propagation

In FGM-PS2, the coating delamination is significantly delayed; the crack propagation is influenced by microstructural features such as pores and intersplats defects [9].

pores

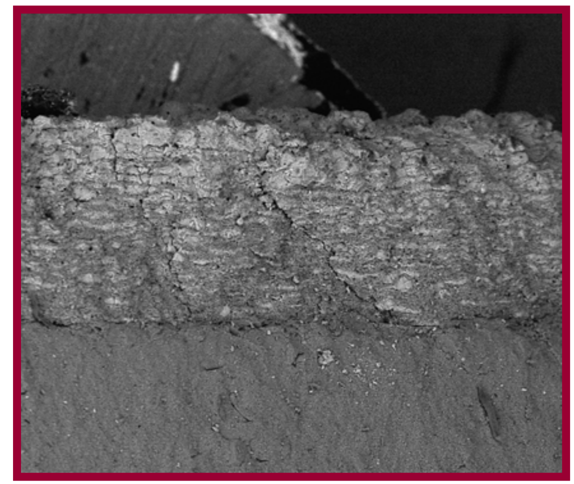
alumina

glass

cracks

Coating-substrate interface

120 μm



1400 μm

In fact, FGM-PS2 is thinner (experiences lower residual stresses than FGM-PS1) and presents some glass next to the interface (matching agent) [9].

Conclusions

FGMs are really complex systems: they are multi-phase materials, with a peculiar compositional and microstructural variation in space.

To faithfully predict the properties and performances of FGMs, a suitable computational tool is required, which is able to account for the microstructural features of such graded systems (distribution of the constituent phases; pores; interfaces; etc.).

Thanks!

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