Structural Analysis of a Pressure Sensor for High Temperature Environments

S.V. De Guido[1], G.S. Masi[1], P.V. Miodushevsky[1], L. Vasanelli[2]

[1]Department of Innovation Engineering, University of Salento, Via Monteroni, 73100 Lecce (Italy)
[2] Department of Mathematics and Physics E. De Giorgi, University of Salento, via per Arnesano, 73047 Monteroni (Le), Italy

*stefano.deguido@unisalento.it

Abstract: Control of the environment conditions is necessary for many important industrial sectors, but currently it is difficult, measuring pressure in high temperature environments. In fact pressure sensors operating at temperatures higher than 500°C are absent in the world market. Our goal is to develop a pressure sensor that can operate at the high temperature up to 700°C.
A structural analysis on the case has been performed to design it and to study the behavior with pressure and temperature of different metallic alloys, Steel 316L, Inconel 718 and Ti6Al4V; all of them largely used in aeronautics. This analysis was performed using a model reckoning with the mechanical stress due the pressure combined with the thermal expansion of the material. In particular the displacement of the top of the pole and the stress on the membrane were investigated. The results of the stress were compared to the yield strength of the considered alloys in order to calculate the Factor of Safety.

Keywords: Pressure sensors, high temperature, stress, Factor of Safety

1. Introduction

Important sectors of aerospace, automobile and energy industries require sensors that can provide reliable measurements in high temperature environments, for example pressure sensors for gas turbines. Very good semiconductor sensors are available for measuring pressure, but the behaviour of semiconductors substantially changes with temperature and then they are not reliable over 500°C.
A sensor that can provide reliable measurements at higher temperature must rely upon materials whose characteristics does not change dramatically with temperatures.
Our High Temperature Pressure Sensor (HTPS) will made be made up of a ceramic sensible element and a metallic case. The sensible element will be a ceramic beam with a Weathstone bridge on its surface. A CAD representation of a section of our design is in Figure 1.

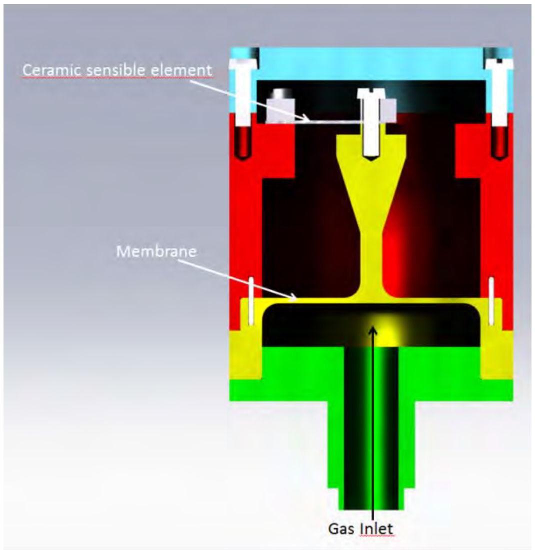

Figure 1 Section of the CAD design of the sensor

The gas, entering the lower part of the sensor will warp a plate, pushing the pole set upon it. The end of the sensible element, with an end fastened to the top of the pole, will undergo an s-shape bending. Figure 2 shows a COMSOL elaboration of the stress tensor on the surface of the sensible element. In Figure 2 we have encircled two areas: the blue represents the maximum compressive stress, the red the maximum tensile stress. In each region the stress is uniform. The bridge resistors will set up in these two regions and connected to sum the changes of their resistances.

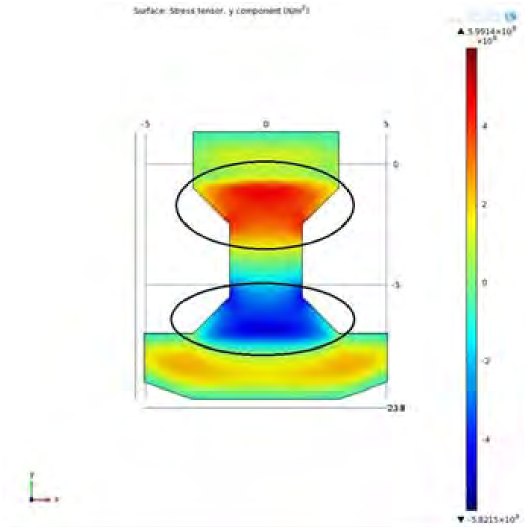

Figure 2 y-component (longitudinal dimension) of the stress tensor calculated with COMSOL

In this paper we will concentrate on the most stressed part of the sensor, the yellow one in Figure 1, the piston made up of the metallic plate and the pole. A structural analysis of the metallic plate, has been performed to design the case and to study the behaviour with pressure and temperature of different metallic alloys, Steel 316L, Inconel 718 and Ti6Al4V; all of them largely used in aeronautics.

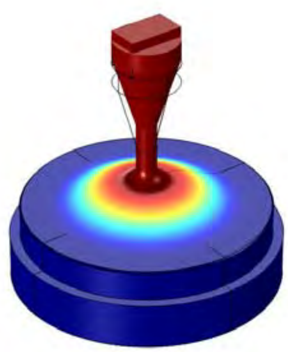

Figure 3 A COMSOL Multiphysics rendering of the piston deformed by a pressure of 4 bar

We will describe in this paper the displacement of the top of the pole and the stresses on the plate due to pressure and thermal expansion.

2.Theoretical model and numerical simulation

In order to have a reliable response of the sensor to the pressure loads it is necessary that plate maintains its elasticity and then that the stresses should be kept under the yield strength limit.
There are two sources of stress: warping by pressure and thermal expansion. In designing the sensor it is necessary to know the limits of pressure and temperature the plate can withstand without losing its elasticity; using a finite element analysis it is possible to study the critical levels of pressure and temperature and the best material for fabricating the case according the environmental conditions in which the sensor would work. So we elaborated a theoretical model reckoning with the mechanical stress due the pressure combined with the thermal expansion of the material.
The calculations was based on finite element method (FEM) and carried out by using COMSOL Multiphysics 4.2a.
We studied the stationary conditions, not considering in this study transients; then the results are reliable for slow changes of pressure and temperature.
In elastic regime we have [4]:

$$-\nabla \cdot \boldsymbol{\sigma} + \boldsymbol{F} = \rho \ddot{\boldsymbol{u}} \quad (1)$$

with $\boldsymbol{\sigma}$ stress thensor, $\boldsymbol{F}$ body force, ρ the density of the material, $\boldsymbol{u}$ the displacement vector and the two dot indicates the second derivative. In conditions of equilibrium $\ddot{\boldsymbol{u}} = 0$.
The strain-displacement equation is:

$$\boldsymbol{\varepsilon} = \frac{1}{2}[\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T] \ (2).$$

where ε is the strain.
The Hooke's law relates the stress tensor to the strain tensor:

$$\boldsymbol{\sigma} = \boldsymbol{C} : \boldsymbol{\varepsilon} \quad (3)$$

$\boldsymbol{C}$ is the elasticity tensor.
For isotropic materials (metals are isotropic) (3) is:

$$\begin{pmatrix} \sigma_x \\ \sigma_y \\ \sigma_z \\ \tau_{xy} \\ \tau_{xz} \\ \tau_{yz} \end{pmatrix} = \frac{E}{(1+\nu)(1-2\nu)} \begin{bmatrix} 1-\nu & \nu & \nu & 0 & 0 & 0 \\ \nu & 1-\nu & \nu & 0 & 0 & 0 \\ \nu & \nu & 1-\nu & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1-2\nu}{2} \end{bmatrix} = \begin{pmatrix} \varepsilon_x \\ \varepsilon_y \\ \varepsilon_z \\ \gamma_{xy} \\ \gamma_{xz} \\ \gamma_{yz} \end{pmatrix}$$

(4)

Where $\sigma_x, \sigma_y, \sigma_z$ are the normal stress components, $\tau_{xy}, \tau_{xz}, \tau_{yz}$ are the shear stress components, $\varepsilon_x, \varepsilon_y, \varepsilon_z$ are the strain components $\gamma_{ij} = \frac{E}{2(1+\nu)}\tau_{ij}$, E is the Young's modulus and ν the Poisson's ratio.

In our model z-axis is parallel to the longitudinal axis of the pole.

A change in uniform temperature applied to an unconstrained, three-dimensional elastic element produces a expansion. Free thermal expansion produces normal strains that are related to the change in temperature by

$$\varepsilon = \alpha \Delta T \quad (5)$$

where is α the thermal expansion coefficient, and ΔT the change in temperature.

Equation (3) becomes:

$$\boldsymbol{\sigma} = \boldsymbol{C}: \left[\boldsymbol{\varepsilon} + \boldsymbol{\alpha}\left(T - T_{ref}\right)\right] \quad (6)$$

For the values of the parameters E, ν and α we referred to [6-12].

In our simulation we imposed that the bottom surface of the inlet tube could not move in z direction (the longitudinal axis of the pole) but all the components could expand in all directions.

In order to find out the best material among the ones investigated, at the end we will calculate the Factor of Safety as the as ratio between Yield Strength and the maximum stress value in order to know which are the limits of the elastic regime.

3. Simulation results

As first step we wanted to define the optimal thickness of the metallic plate, so we performed a simulation calculating the displacement of the top of the pole (this movement will cause the s-shape bending of the ceramic beam) and the stress of the plate for different values of plate thickness. In figure 4 the results of the displacement of the top of the piston as a function of the membrane thickness at 25°C and a pressure of 4 bars are shown. The titanium alloy allows larger displacements than Inconel and Steel, this could be useful for a higher sensitivity device.

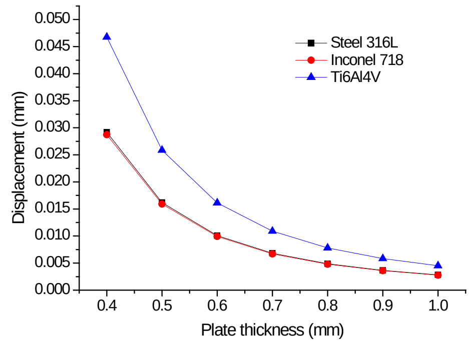

Figure 4 Displacement as a function of the plate thickness at a temperature of 25°C and 4 bar pressure

At 700°C, as shown in figure 5, the behaviours of the three materials differ considerably and for all the alloys there is a large increase of the displacement of the piston if compared with the case of 25°C.

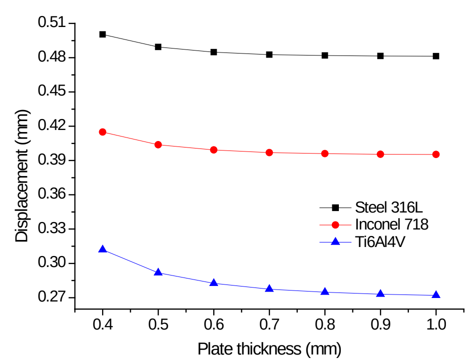

Figure 5 displacements as function of the plate thickness at 700°C and 4 bar

The large growth of the displacements is principally due to the thermal expansion. In fact turning down the pressure to 0 bar, we could isolate the thermal contribution; the results are reported in figure 6.

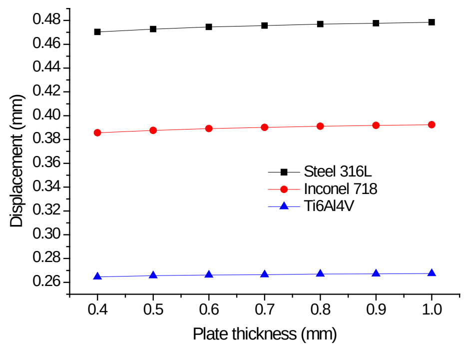

Figure 6 displacement of the piston-top at 700°C without any pressure load

Comparing the graphs in figure 5 and figure 6 we see that the displacement has a little contribution of the pressure. In order to know the real part of the displacement due to the pressure we have to subtract the thermal part from the total displacement. The result is shown in figure 7. The graphs are quite similar to the ones obtained for 25°C.

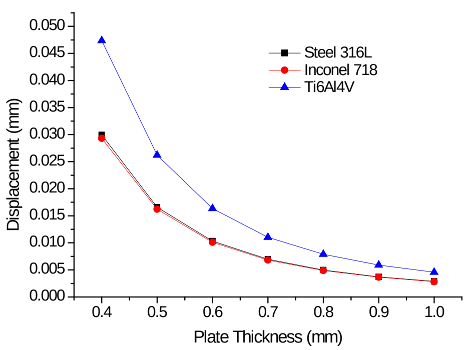

Figure 7 displacement due to only the pressure load at 700°C

The contribution of the thermal expansion is an order of magnitude higher than the pressure contribution. This is an important indication for us to investigate the stress introduced by the temperature growth.

For this reason we calculated also the stress on the plate in different thermal conditions. In figure 8 maximum stresses for a pressure of 4 bar and a temperature of 25°C versus the plate thickness are reported. The values are very similar for all the alloys, the graphs of Inconel and Steel coincide.

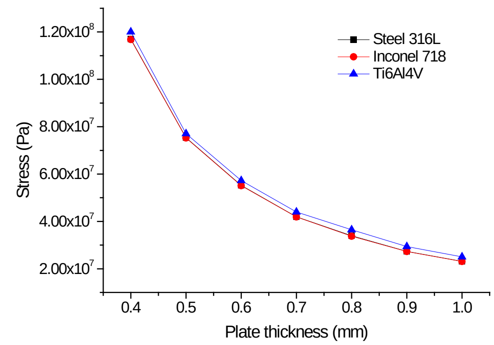

Figure 8 maximum plate stresses at 25°C and 4 bar pressure

We performed the same study for a temperature of 700°C, obtaining the graphs in figure 9. These values are much higher than the ones at 25°C, above all for Inconel and Steel. These two alloys show a minimum for stress at 0.5 mm, while Ti6Al4V shows a descending trend 0.4 to 0.7 mm, but the difference of the stress value at 0.5 mm and at 0.7 mm is only 7.1×10^{6} Pa, with an absolute stress at 0.5 mm of 1.5036×10^{8} Pa, the stress decrease is less than 5% from 0.5 to 0.7 mm. So we decided to continue our study for a thickness of 0.5 mm for all the alloys.

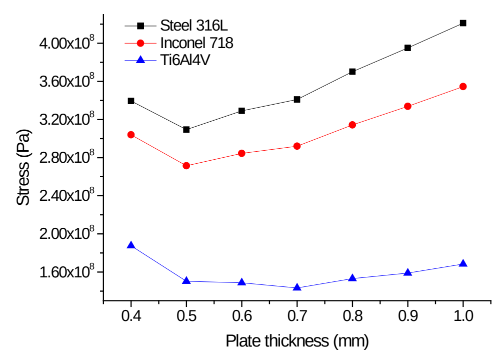

Figure 9 maximum plate stresses at 700°C and 4 bar pressure

As before we calculated the contributions to the stress due to the pressure load and to the thermal expansion. Figure 10 shows the stresses due to the pressure load only. Comparing these values of stress with figure 8 we see that the pressure stress is unaffected by the thermal conditions.

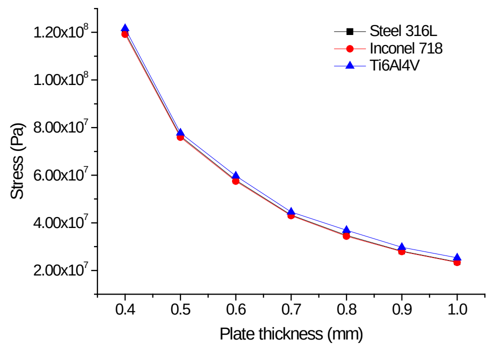

Figure 10 stress due to only the pressure at 700°C

Knowing the maximum stresses we can compare these with the yield strength.
For the steel and Inconel it was easy to find the yield strength values in the temperature range 25 to 700°C. Finding the yield strength for Ti6Al4V was more difficult, above all at high temperature. We considered the data reported in [11], but the higher temperature, in this case, was 350°C. We fitted the data obtaining the curve equation:

$$Y = 8.48648 \cdot 10^8 - 8.7496830225 \cdot 10^5 \cdot T + 292.6404 \cdot T^2 \quad (7)$$

in which Y is the yield strength and T is the temperature (in Celsius). obtaining an optimal correlation with the data reported in [11] (R^2=1) and the yield strength at 700°C calculated with this equation is $3.80 \cdot 10^8$ Pa.
In Table 1 are reported the values of yield strength we used to calculate the Factor of Safety (FoS) as ratio between yield strength and the maximum stress value.

Table 1 Yield Strengths at 25°C and 700°C

Alloy	Yield Strength 0.2% a 25°C [MPa]	Yield Strength 0.2% a 700°C [MPa]
Steel 316L [1],[13]	290	135
Inconel 718 [2], [14], [15], [16]	1100	903
Ti6Al4V [3]	827	380

In figure 11 are shown the FoS calculated from the yield strength of table 1 and the stresses at 25°C and 4 bar pressure for the three alloys. The FoS has high values for Inconel and Titanium alloy even for thin plates, 9 for Inconel and 7 for Ti6Al4V for 0.4 mm thickness. The steel has appreciably lower FoS values at any thickness.

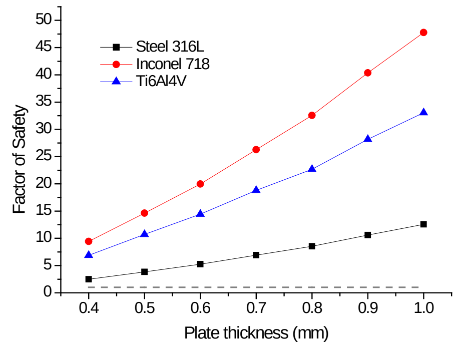

Figure 11 FoS versus Plate thickness at 25°C and a pressure of 4 bar. The grey dashed line indicates FoS=1

Figure 12 shows the FoS at 700°C with a pressure of 4 bar. According to the growth of the stresses and the lower yield strength, the FoS values are much lower than the ones at 25°C.

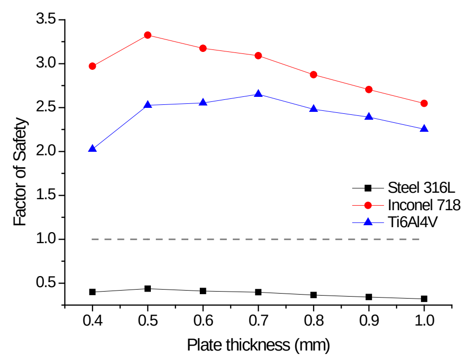

Figure 12 FoS versus Plate thickness at 700°C and a pressure of 4 bar. The grey dashed line indicates FoS=1

The FoS of the steel is less than 1 for any considered thickness. Inconel and titanium alloy remain in the elastic regime. In fact, in the considered range, for the nickel alloy there is a maximum, 3.5 for 0.5 mm and a minimum of about 2.5 at 1 mm thickness; for the Ti6Al4V the FoS is a little bit lower, a minimum of 2 for 0.4 mm and a maximum of 2.65 for 0.7 mm.

4. Conclusions

Inconel 718 is, among the investigated alloys, the one that permit to have a higher elastic limit for high temperatures thanks to the low reliance of its yield strength on temperature.
The Ti6Al4V is the one with the higher lowering of the yield strength with growing temperature, but it is also the one with the smaller stresses in any thermal condition and then the elastic limit is not trespassed. Moreover it shows a lower Young's modulus and then higher displacements of the pole and this could allow to have a higher imbalance of the Wheatstone bridge and then a larger sensitivity for the sensor.
The Steel is not reliable for high temperatures because the thermal stress because even without applying any pressure its yield strength is exceeded.

5. References

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