Applying CFD in Manufacturing of Polymer Composite Reinforced with Shape Memory Alloy via Resin Transfer Molding Process

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ABSTRACT

This paper aims to study the manufacturing process of polymer composite reinforced with shape memory metal alloys by RTM process using ANSYS CFX® software. The mathematical modeling consists of mass and momentum conservation equations applied to a metal mold with dimensions 0.3 × 0.3 × 0.002 m^3 containing ten NiTi alloy wires 0.0005 m diameter. Results of the flow front position of the resin (polyester resin mixed with calcium carbonate particles), pressure, streamlines and resin velocity fields during the process are presented and discussed. We conclude that the addition of calcium carbonate resulted in increased resin viscosity and greater inlet pressure obtained at the entrance of the mold which resulted in short time to full fill the mold and the highest pressures at the NiTi alloy wire surface were obtained in the central region and near the mold entrance..

1. INTRODUCTION

Over the centuries, the evolution of knowledge has been clearly linked to the improvement and development of new materials. This continuous evolution, however, has demanded increasingly resistant material and with low density [1].

Automotive and aeronautics industries have turned increasingly to the development of materials that combine good mechanical properties and low density, in order to improve the performance of their products, giving them new applicability. In this context, more and more studies in the field of composite materials have been made, because of its extensive applicability and combination of properties.

Composite is defined as any multiphase material that exhibits a significant proportion of the two phases that constitute it, such that a better combination of properties can be obtained. They consist generally of a continuous phase called matrix and a discontinuous phase, the reinforcement [1,2]. In general, composites are designed to obtain a set of properties that none of the conventional materials individually contain such as low electrical conductivity, high modulus of elasticity, low density, which can be manufactured in different colors and shapes, high strength to chemical corrosion, low maintenance cost and high mechanical strength [3].

Currently, the composite materials with specific properties allow producing components of reduced weight with high values of rigidity and mechanical resistance. With an improvement

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of these materials, it is natural that the composite manufacturing processes have improved, thus promoting the optimization of their properties [4].

Among the various techniques of composite manufacturing, the process of resin transfer molding (RTM), have gained prominence due to the advantages over other manufacturing processes, including lower cost of production, uniformity of mechanical characteristics and good surface finish of parts obtained [5,6,7]. This technique involves the injection of a thermosetting resin in a closed mold in which a preform was placed previously [8]. This mold must have at least one resin injection port and an outlet port to allow, during injection of the resin, the air flow to outside of the mold [9].

Even with all of visibility that the composite materials have gained in the recent decades, some metallic materials, in particular shape memory alloys, have gained visibility due to its properties of the phase transformation which occurs in the alloy. Shape memory alloys are special metallic materials which possess the surprising ability of recover a plastic deformation or "elastic apparently" through a subsequent heating above a critical temperature [10]. This effect is due to phase changes in the solid state, the martensitic and austenitic type that are phases found in the alloy, so that the martensitic phase is the phase found at low temperatures and has a very ductile monoclinic crystalline structure that is easily deformable, while the austenitic phase is formed at high temperatures and has a cubic crystal structure, with a different mechanical behavior [11].

When embedded in the polymer matrix, the shape memory alloys show different behavior as compared alone. Then, as the wire inside the composite may not recover its original shape generates within the matrix which may lead to changing the shape and vibration natural frequency of the composite. The introduction of shape memory alloys with a diameter between 0.075mm and 0.6mm into a polymer matrix, it has the advantage of incorporating low mass to the system can increase its stiffness or cause a significant change in its shape [12,13].

The combination of composite materials and alloys with shape memory produce what we call smart materials. The intense use of conventional polymer matrix composites, allowed during the last decades, the development of smart composites with memory shape alloys embedded. As established the manufacturing and marketing of shape memory alloys wires, has turned possible its use in composites [3,14]. Obtaining these intelligent materials allows a set of new opportunities and technological innovation, since more resistant materials, with low density and some degree of functionality controlled by environmental parameters such as, temperature and magnetism fields, can become an industrial reality in the near future [15].

The advancement of resins development, fillers and chemical additives have promoting research that transform the way like RTM technique is applied in order to obtain structures with higher mechanical properties. In this sense, this paper aims to numerically study the mechanical forming process of polymer composites reinforced with NiTi alloys via RTM technique by using ANSYS CFX® commercial software.

2. METHODOLOGY

2.1. Problem description

The study domain consists of a three-dimensional metal mold ($0.3 \times 0.3 \times 0.002$ m³), which were positioned ten NiTi wire with 0.0005 m diameter and divided into two groups of five equidistant wires, in right and left sides of the entry of the mold, which is located in the center of the down face of the mold. On the upper face, it is located four output parts of the mold. Figs. (1) and (2) show a 3D view of the metal mold and the disposition of the wires along the mold.

2.2. Numerical grid

For numerical analysis of the resin injection process in the mold, it is necessary to transform the study domain in a set of elements, so called numerical grid [16]. The numerical grid was developed from the geometry of the mold using the ANSYS ICEM CFD commercial software, where we used the blocking method. A large block have been generated and "broken" according to the needs of the geometry. The mesh generated was refined in the regions of interest that are input, the outputs and the walls of the wires. The purpose of this refinement, namely, the increasing the number of element in these areas is to obtain the most accurate possible numerical results. The final grid has 590265 elements and 672832 nodes. Fig. (3) illustrates the refinement performed at the entry and exit regions of the mold, respectively.

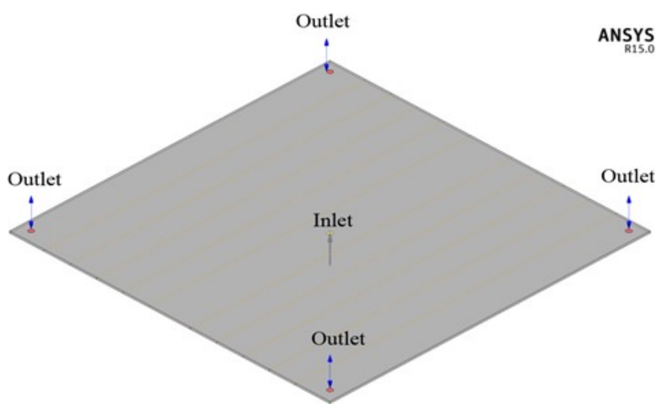

Figure 1: 3D view of the metal mold with the alloy wires and inlet and outlet parts positioned along the plate.

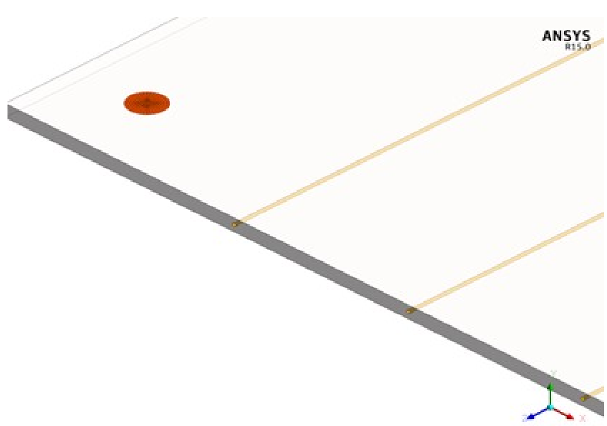

Figure 2: Details of the outlet and disposition of the wires along the mold.

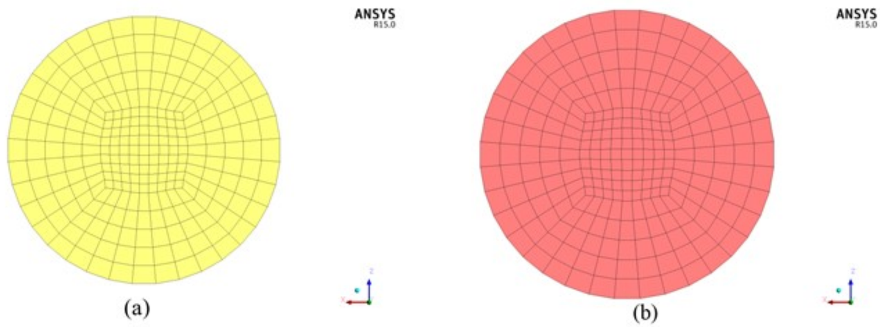

Figure 3: Details of the refinement performed at the (a) inlet port and (b) outlet port of the mold.

2.3. Mathematical modeling

The basic equations that describe the fluid flow phenomena are defined by physical laws of mass and momentum conservation.

The three dimensional multiphase flow mathematical modeling, is composed by the following equations:

- Continuity equation:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha) + \nabla . (r_\alpha \rho_\alpha \vec{U}_\alpha) = \vec{S}_{ms\alpha} + \sum_{\beta=1}^{N_\rho} \Gamma_{\alpha\beta} \quad (1)$$

- Momentum equation:

$$\frac{\partial}{\partial t}(r_\alpha \rho_\alpha \vec{U}_\alpha) + \nabla . [r_\alpha(\rho_\alpha \vec{U}_\alpha \otimes \vec{U}_\alpha)] = -r_\alpha \nabla p_\alpha + \nabla . \{r_\alpha \mu_\alpha [\nabla \vec{U}_\alpha + (\nabla \vec{U}_\alpha)]\} + \sum (\Gamma^+_{\alpha\beta} \vec{U}_\beta - \Gamma^+_{\beta\alpha} \vec{U}_\alpha) + \vec{S}_{m\alpha} + \vec{M}_\alpha \quad (2)$$

The sub-index α is the phase indicator on the resin-ar two-phase flow, r, ρ, μ and $\vec{U}$ are, respectively, volume fraction, density, dynamic viscosity, and velocity vector, and p is the pressure, $\vec{S}_{m\alpha}$ is the term of the external forces acting on the system per volume unit. In the term referring the momentum transfer induced by interfacial mass transfer (third term on the right side of the equation) the subscripts α and β correspond to the phases involved. Γ^+ corresponds to the mass flow rate per volume unit of the β phase to α phase and vice versa, $\vec{M}_\alpha$ describes the overall strength per volume unit (interfacial drag force, lift force, wall lubrication force, virtual mass force and turbulent dispersion force) on the α phase due to interaction with the β phase [17].

2.4. Boundary conditions

At the beginning of the injection process, the mold is full filled with air. In the mold inlet, polymeric resin is injected mixed with calcium carbonate mineral filler (CaCO3). In the four outputs located on the surface opposite to the mold inlet, there will be a flow of air present inside the mold as the resin invades the mold until fill it completely. To complete the mathematical model, the following boundary conditions were adopted:

- In mold input section, was admitted superficial velocity 0.5 m/s, resin (plus calcium carbonate) volume fraction 1.0, and air volume fraction null;
- No slip condition to the side, top, and bottom of the mold (does not include the input and outputs);
- NiTi alloy wire were studied as a solid domain present in the mold, being the mold cavity considered domain of continuous phases due to the relationship between the total volume of the mold and the volume occupied by the wires be not small enough to characterize a porous volume.

2.5. Case studied

The study evaluated the flow front position of the resin into the mold so that the mold is completely filled. For this purpose, the resin was studied with mineral filler ($CaCO_3$). Tab. (1) summarizes the properties used in the simulation.

Table 1: Physical parameters of the polyester resin containing calcium carbonate [18].

Properties	Units	Values
Viscosity	[cP]	1414
Density	[g/cm³]	1.32
$CaCO_3$ content	[%]	20
Temperature	[°C]	25

3. RESULTS AND DISCUSSION

3.1. Resin volume fraction fields

The evaluation of the volume fraction fields is an ideal tool to identify the total filling of the mold by the resin and consequently the possible occurrence or unwanted formation of air bubbles into the composite. When working with transient process, it is possible to assess the resin advances within the mold, which may assist both to verify the resistance of mold to fluid flow which is related to production volume setting in order to optimize molding process, or the adjustment of process input parameters. Fig. (4) exhibit the advancement of the resin into the mold. We have a radial behavior of the resin volume fraction. In this case, there is a registered frame every 5 seconds of filling. It is possible to observe the velocity at which the resin enters the mold. The resin advances in the mold until to touch the walls of the plate have occurred in until 15 seconds. Between 20 and 25 seconds, the resin quickly full almost fills the mold. The presence of the wires affects the behavior of the front of the resin, causing small disturbs in the fluid flow.

Fig. (5) illustrates the volumetric fraction of the resin along the vertical direction of the mold, in three planes located at Y=0.000 m; 0.001 m and 0.002 m at the instant of 40 s of injection. After analysis of the figure we can see that the presence of the wires arranged along the mold causes additional difficulty in the flow of the resin. Thus, entrainment of the air inside the mold occurs, especially in the upper surface plane. This physical situation is undesirable. The presence of air bubbles in the post-cure composite generates defects that reduce the mechanical properties of the material. These results can not be seen in a two-dimensional analysis. At time t=40s, a mass flow rate of resin at the inlet and outlet of the mold is 0.010843 kg/s and 0.010742 kg/s, respectively.

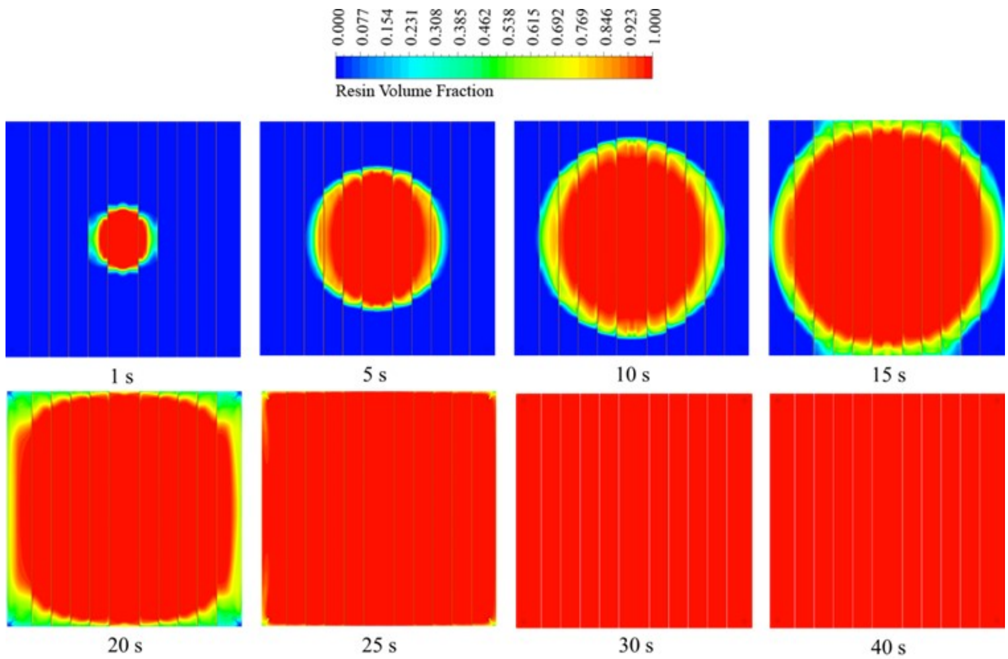

Figure 4: Advancement of the resin during the injection process until to reach total filling of the mold.

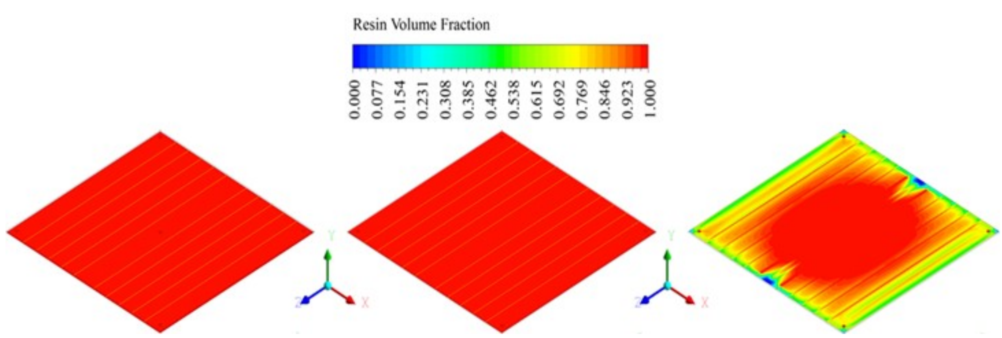

Figure 5: Volume fraction distribution of the resin in t=40 s of injection process at different planes.

The advance rate of the resin is another important parameter to the success of the RTM molding. Injection process with lower velocity is good; the flow must be as laminar as possible, to avoid stirring the mold cavity and thus produce composites without defects and discontinuities.

A method of evaluating the resin forward velocity in the mold is through the streamlines, which indicate the path of the particle [19]. Fig (6) illustrates the streamlines at different times. After 1 second (the first frame), the flow has not yet found the side of the mold, so it is possible to clearly observe the laminar flow region of the resin and the air flow region. After 5 seconds (second frame), it is noted that streamlines adopt a more linear radial behavior, due to the further advancement of the resin into the mold, which provokes the exit of the air. In third frame the streamlines are arranged so broadly similar to the second frame. In the fourth frame, the molding was virtually full filled, and the flow lines have adopted their final behavior (steady state).

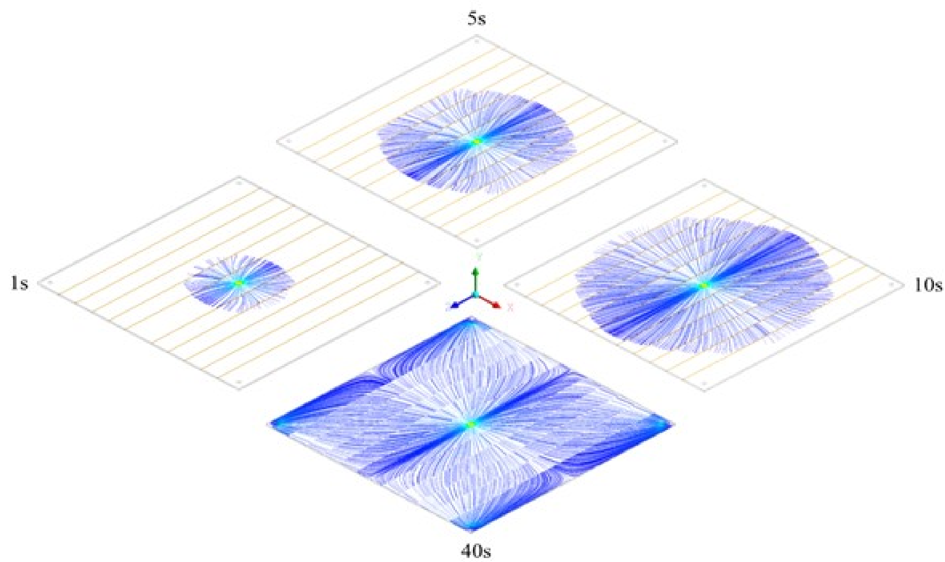

Figure 6: Streamlines at different moments into the mold.

Fig. (7) illustrates the streamlines near the mold inlet and on the region surrounding the wires. Fig. (8) shows the same result in the form of a vector field. It is noticed that at the entrance of the mold, the resin initially flows in the vertical direction and then moves horizontally. In the horizontal direction, the resin flows around the wires, with symmetrical behavior and approximately as the potential flow (non-viscous flow). This is due to the low velocity of the resin in this region, which was less than 0.1 m/s.

By analyzing the flow around the wires, one can make some fundamental comments:

a) The fluid (resin) in the stream is at rest at the point of frontal stagnation, which causes a rise in local temperature;
b) From the stagnation point (zero velocity point), the pressure decreases along the wire surface and in the direction perpendicular to the radial direction, which provides a development of the boundary layer under the effect of a favorable pressure gradient (the tangential velocity increase), until it reaches a minimum value (maximum tangential velocity). From this point, the boundary layer develops in the presence of adverse pressure gradient providing a redirection in the aceeleration of the resin (the tangential velocity decreases);

c) The flow around the wires strongly influences the drag force acting on it self and in the direction of the flow. This force is composed of two components: one due to shear stress in the fluid, at the surface of the wire, called a friction drag, and another due to the pressure variation in the flow direction along the surface of the wire, which is resulting of the formation of the wake in the back fale of the wire (form, or pressure drag).

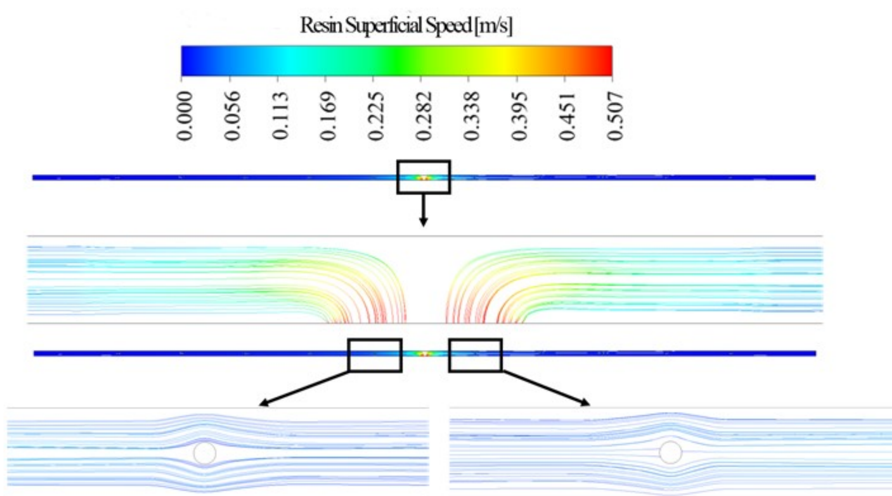

Figure 7: Streamlines near the mold inlet.

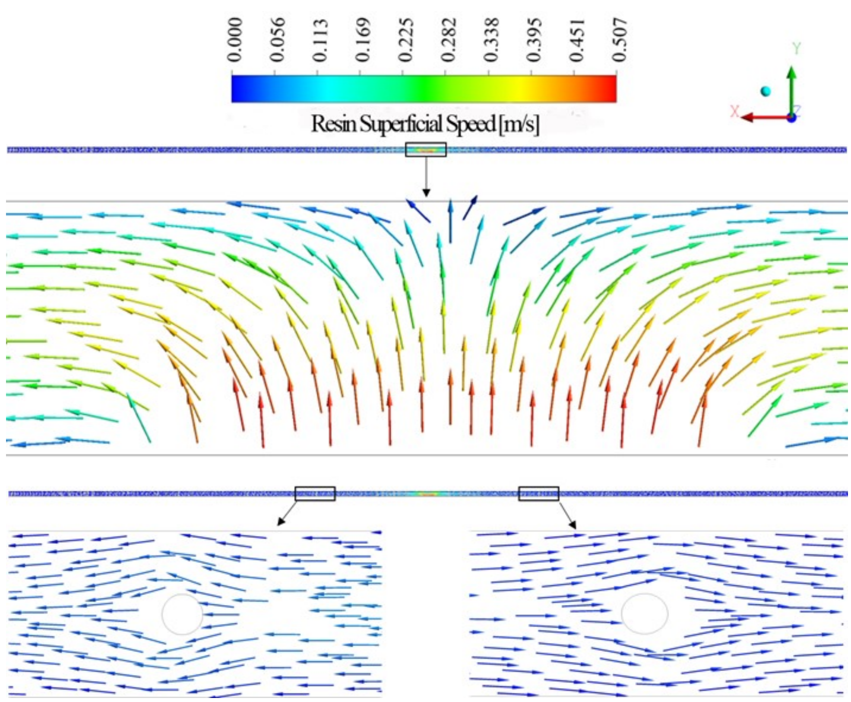

Figure 8: Velocity vector field of the resin near the mold inlet.

3.2. Injection pressure variation

The pressure is a fundamental parameter during the process of resin transfer molding. Although this is a common input parameter in the process of RTM, it was decided to choose in the present study an entry velocity as boundary condition. The evaluation of the input pressure allows obtaining a curve of this parameter along the time, where it is possible to determine the injection pressure in a real situation. Fig. (9) shows graphically the pressure curve for the case studied as a function of mold filling time.

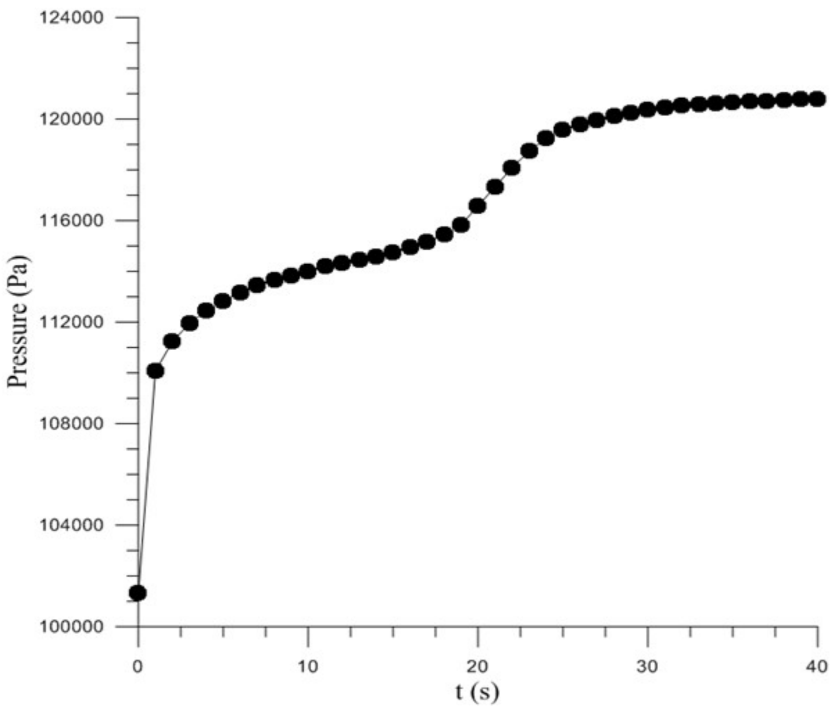

Figure 9: Variation of the resin injection pressure in the inlet part as a function of filling time.

From the analysis of the pressure along the time we can see a continuous increase in this parameter provoked by the amount of resin into the mold which increases in time which difficult the resin flow front advances. After 40 seconds the injection process reach its steady-state condition (P=120.809 kPa).

Fig. (10) shows the pressure distribution at the surface of NiTi alloy wires at time t=40s. It is verified that the highest pressure in the wires occurs near the entrance of the mold, with a value approximately 113674 Pa. It is in this region that the maximum drag force occurs, which will generate deflection in the wire, causing mechanical tension and deformation thereof. This deformation may be permanent depending on the curing time and viscosity of the resin. That is, the wire will be deformed after resin solidification. Thus, caution is advised regarding mold filling containing shape memory alloy wires, especially, if it is in the martensitic state at low temperatures, where shape change may lead to changes in the natural vibration frequency of the composite [12, 15].

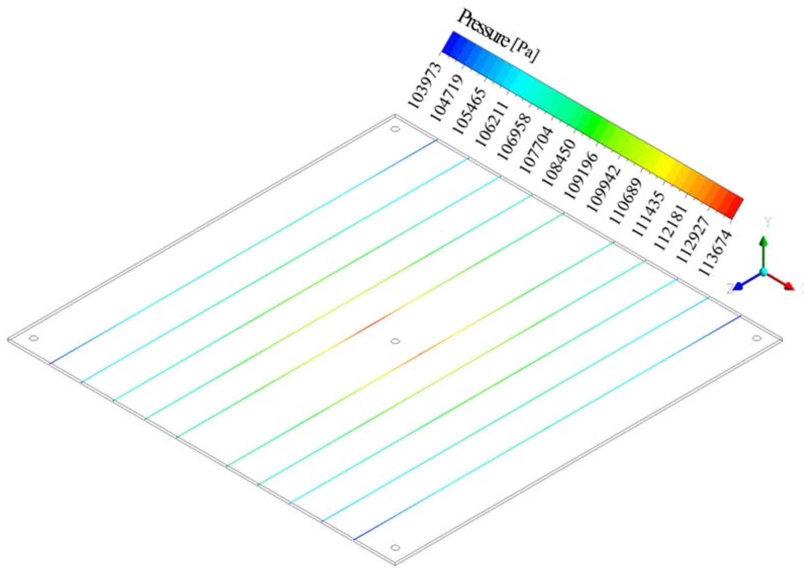

Figure 10: Pressure distribution at the surface of NiTi alloy wires at time t=40s.

4. CONCLUSIONS

The case study presents behavior particular fluid dynamic. From the analysis of the obtained results we can conclude that:

a) The flow front of the resin, during filling of the mold, resulted in a radial behavior. With the addition of calcium carbonate (20%), the time for the resin to full fill the mold is 40s;
b) It was observed that the resin with the addition of the mineral had enough interaction with the air inside the mold during the injection process. This resin-air interaction resulted in a composite with poor quality, since it prevented air bubbles mean the surface;
c) The increase in resin viscosity caused by the addition of a mineral component led to a high injection pressure at the mold inlet, which resulted in small time to full fill the mold. The pressure increased with the time of injection;
d) The highest pressures at the NiTi alloy wire surface were obtained in the central region and near the mold entrance. In this region occup the highest drag force on the wires, whose action can deform the wire producing mechanical stresses, which, depending on the intensity can broken the wire;

It is necessary to evaluate experimentally the studied case, adopting the highest values of injection pressure at the entrance of the mold, to validate the results numerically.

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