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THERMAL INFLUENCE OF 6351 T6 ALUMINUM ALLOY WITH SPHERICAL AIR INCLUSIONS

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Abstract. Understanding the heat transfer phenomenon through geometry with the insertion of other elements is a concept of disturbing questions. The work accomplished proposes issues that come to the encounter of these questions when evaluating thermally the influence of air inclusions in an aluminum alloy 6351 T6. The specimen used in this work may be associated with composite materials due to the two phases' composition in their geometry. Such materials have been widely used in industry because of their beneficial properties that are potentiated giving a higher yield to the applications. To obtain the largest number of data, four specimens were made in which analyzes were performed by the finite element method, executed in ANSYS software, and an experimental evaluation performed in a manufactured apparatus according to the needs founded. The results were submitted to statistical analyzes to prove their veracity. By Analyzing the temperatures found in the test, it is possible to identify that the difference between the size of the air inclusions and their geometric distribution has significant interference in what involves heat transfer. This work may contribute to future studies on heat transfer in porous structures or geometries with inclusions of other materials.

Keywords: aluminum alloy, thermal analysis, finite element method, heat dissipation.

1. INTRODUCTION

The search for energy efficiency has made the study of heat transfer a fundamental area in engineering related to industrial development. This research field has been improved since the time of Fourier (1768-1830) who has developed experimental and theoretical work of heat transfer.

The importance of this type of work is due to several processes that use energy in transit. According to (ÇENGEL; BOLES, 2013) this energy transfer is due to the difference of temperature between two regions in the same medium and could be represented by partial differential equations that are denominated by heat equations, and determinates the temperature distribution in a body. These equations are solved by numerical methods.

Many modern technologies require materials properties with non-usual combinations, which cannot be met by metallic alloys, ceramics, or other conventional polymeric materials. This is especially true for materials with aerospace, underwater, and transportation applications. The combinations and the ranges of material properties have been expanded by the development of composite materials. In general, a composite material could be considered as any multiphase material that exhibits a significant proportion of the properties of both phases that make it up, so that a better combination of properties (CALLISTER; RETHWISCH, 2009).

The heat transfer behavior could be observed in two ways, experimental and computational simulations. The most recommended for the financial and operational viability is a computational simulation however for the validation of the computational results it was necessary to perform some experimental tests on a premanufactured bench to observe how the air inclusions distributed in different ways can influence in specimen heat transfer.

Some studies have been developed in this area, (AMANIFARD; BORJI; HAGHI, 2007) have evaluated the heat transfer in porous media, (HUTTER et al., 2011) analyzed the commercial metal foam in comparison to a designed laser sintered device. Because of thermal management in the electronics industry, their fluid permeability and thermal conductivity, (GAUNA; ZHAO, 2017) have simulated numerically the heat transfer in porous metals for cooling

applications, in this way (SLATER; STRANGWOOD, 2013) have modeled the effects of pore arrays on the electrical and mechanical properties of copper. Finally (SKIBINSKI et al., 2019) analyze the influence of pore size variation on the effective thermal conductivity of open-cell foam structures with numerical procedures.

This work objective is to perform a computational and experimental analysis in 6351 T6 aluminum alloy with air inclusions in spherical shapes. For samples are analyzed, which each one has a different density due to the number of air inclusions, allowing to observe how each one behaves when exposed to a constant temperature of 80°C.

2. METHODOLOGY

For this paper, the methodology has been divided into two parts, the computational and the experimental analysis. The geometries were developed in a computer-aided design – CAD software for best comprehension and structure analysis and after that manufacturing of specimens.

2.1 Development of 3D solids

Four geometries were developed using the SolidWorks software, by Dassault Systèmes, and the samples were named by the number of spherical air inclusions inserted in them. All the geometries have the same size (50x50x50mm) and square shape.

In the first sample, the massive cube as shown in Figure 1 was developed in order to give parameters for the comparison with the other analyzed solids.
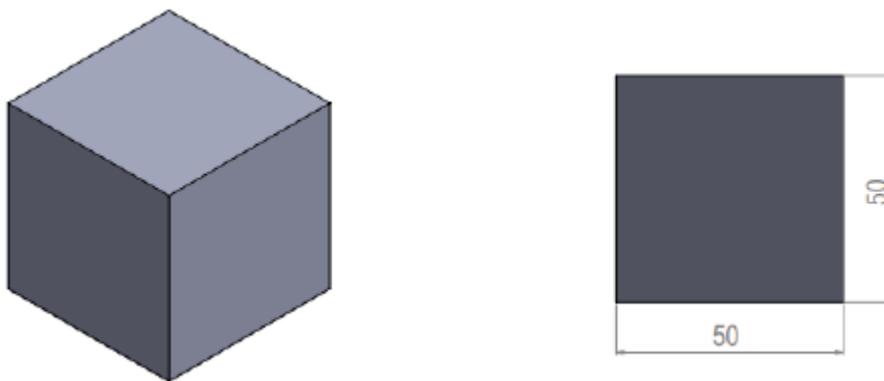

Figure 1. Sample 1, massive cube (author's property)

Sample 2 is characterized by a cube with 15 spherical air inclusions. As shown in figure 2, the sample is compound by four parts. The external parts have 8.5 mm of thickness and five circular incisions with a 15mm diameter in the internal face. The other two parts are compound by 16.5 mm thickness and five semispherical incisions with a diameter of 15 mm on each side. Perforations were made to create the 15 internal spheres in the block.
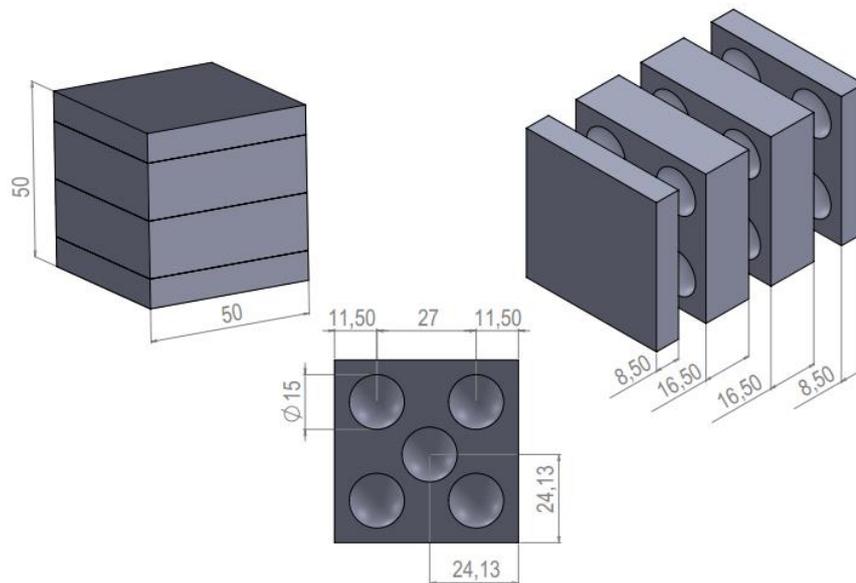
Figure 2. Sample 2, with 15 spherical air inclusions (authors' property)

The third sample, a cube with 27 spherical air inclusions as shown in Figure 3, consisting of 4 parts where two of which are internal with 16 mm of thickness and 9 semispherical incisions on each side with 15 mm of diameter. The external parts have 9 incisions with 9 mm thickness on the internal face with the same 15 mm diameter. The number of inclusions and the size was determined so that in geometry there was a considerable amount of mass as reported by (SLATER; STRANGWOOD, 2013).
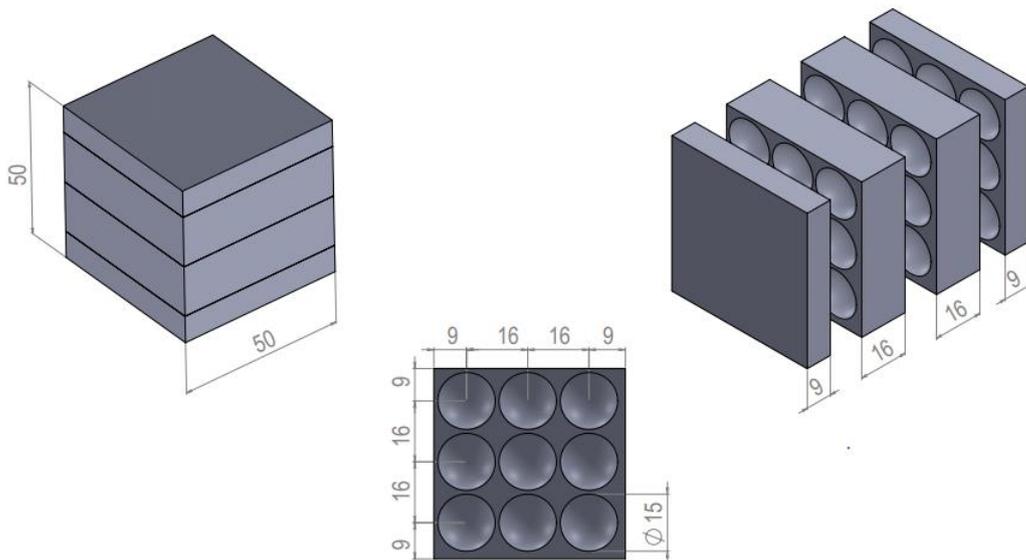

Figure 3. Sample 3, with 27 spherical air inclusions (authors' property)

The fourth and last sample is characterized by a cube with 90 spherical air inclusions as shown in Figure 4. The block was divided into six parts, which the four internal with 9,5 mm of thickness and 18 incisions on each side with 8 mm of diameter. The external parts have 6 mm of thickness and 9 incisions on the internal face with the same 8mm diameter.
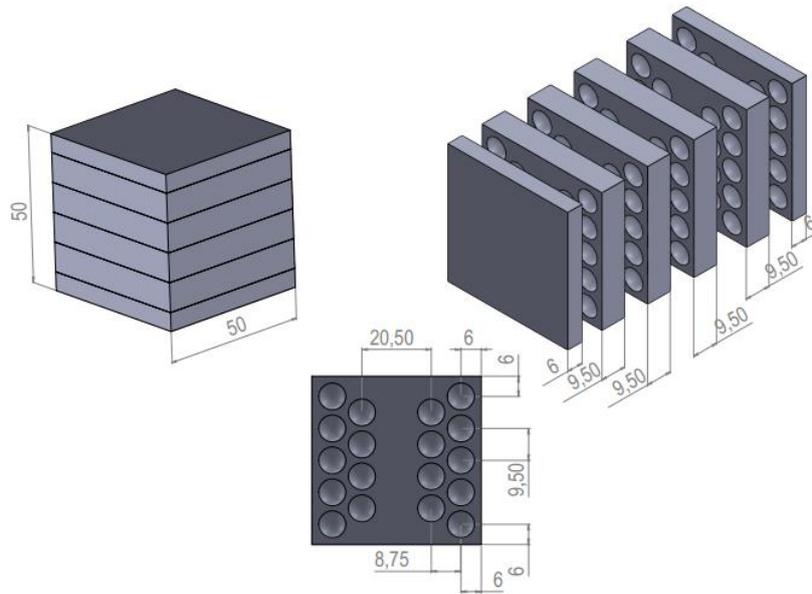
Figure 4. Sample 4, with 90 spherical air inclusions (authors' property)

2.2 Computational analysis

This stage consisted of a thermal simulation in the transient state using ANSYS 18.2 software (ALAWADHI, 2015) and (LAWRENCE, 2002) on the developed geometries in order to analyze the thermal transfer in each geometry separately.

This type of problem is governed by equation 1, where the term that represents the rate of energy storage in the body is described on the right side of the equality. This term is responsible for differentiating a transient analysis from one in a steady state.

$$k\left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2}\right) + q = \rho c \frac{\partial T}{\partial t}$$

where, k = thermal conductivity $(W\,k^{-1}m^{-1})$, t = time (s), T = Temperature (K) ρ = Density of the material $(kg\,m^{-3})$, c= Specific heat of the material $(J\,kg^{-1}\,k^{-1})$ and q = Rate of heat flux (W).

The boundary conditions were the same for all samples. The contact temperature should be 80°C in one face of the cube (side A) and with similar convection of natural air around 5W (side C) and the faces of the cube were perfectly isolated (side B) as shown in Figure 5.
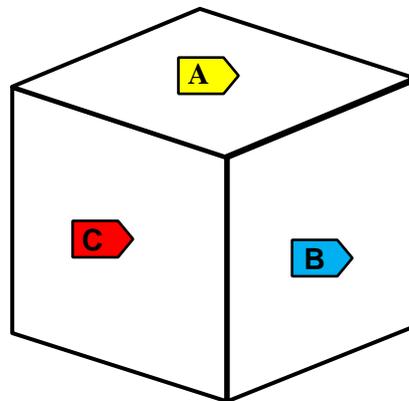

Figure 5. Boundary conditions (authors' property)

Other variables were also taken into account, such as the temperature application time, which was programmed for 300 seconds and the ambient air temperature given as an input 22°C. Table 1 shown the properties of the material.

Table 1. Properties of 6351 T6 Aluminum Alloy

Composite properties	Value	Unit
Specific heat	0,21	Cal g^{-1} °C^{-1}
Specific weight	2,71	g cm^{-3}
Melting temperature	555 – 60	°C
Linear expansion coefficient	24x10^{-6}	L °C^{-1}
Thermal conductivity	184	W m^{-1} K^{-1}

Using the geometry modeled in the program, the meshes were created for the analysis. Different methods were applied to obtain a better quality mesh. For sample 1 the automatic method was used because it does not present any complexity in the mesh generation. For the other samples with the air inclusions, two meshes were used in each sample, one developed for the flat surfaces and another for the internal spheres that represent the inserted air, Hex dominant method, and Multizone method respectively. The mesh quality was defined by the Element Quality tool that evaluates the quality and parameterizes the generated elements.

Table 2 shows the values of the meshes that were used in each sample, always looking at the highest percentage of elements with parameterization above 0.7 in order to generate a high-quality mesh.

Table 2. Mesh convergence

	Sample 1	Sample 2	Sample 3	Sample 4
N° of knots (un)	8281	216671	227555	686129
N° of elements (un)	1728	141993	143463	221396
Mesh creation time (s)	1,5	4	4,44	105
Simulation time (s)	8	228	950	1964
Element quality > 0.8 (%)	100	78,03	83,78	81,32
Final temperature (°C)	42,882	38,560	33,978	44,639

2.3 Experimental analysis

The experimental methodology was governed by the ASTM E1225 standard, which underwent minor changes due to the needs required at work. In order to make the experimental procedure viable, it was necessary to build a specific experimental apparatus.

The experiment consists of applying heat to a face of the block to visualize the heat transfer in the massive specimen and the specimens with air inclusions. The block faces are insulated to avoid exchanging heat with the medium only one face was left exposed, as the computational simulation. The specimens used on this analysis should be the same as the ones that were developed and used in computation analysis, for this were used a circular saw and bench drill. All samples have been sanded and polished to eliminate any irregularities in the machining process. At the end of the treatment a thermal paste was used to guarantee high contact between the plates.

Figure 6 shows the experimental apparatus that has been developed. Because of the size and specifications of the specimens, the apparatus consists of one heated table to transfer the heat for the block, an 12V electrical source that feeds the table. For the temperature control, were used one digital thermostat configured to disarm the relay when 80°C was reached at a heated table and a digital thermometer to monitor the conditions of the specimen, like begging and final temperatures. The temperature sensor was placed on top of the block.

Figure 6. Experimental bench (authors' property)

The experiment was performed in an environment with a temperature initially set at 22°C for all elements. The heated table was set up to maintain 80°C for the time previously stipulated for the test, 5 minutes. This time was chosen according to initial tests, where it was observed that after this period the blocks stabilized the temperature increment with no variation.

3. RESULTS

It was performed a computational analysis with the aim to verify the influence of quantity and size of the air inclusions inside the 6351 T6 aluminum alloy. An experimental test was performed too, with an experimental apparatus developed especially for the problem approach in this research. Several procedures gave the result reliability and thus an average with the values obtained at the end of each simulation was calculated.

A comparison of results was executed where it is possible to observe the different temperatures and heat flow in each geometry, given the size and quantity of the air spheres. Figure 7 to Figure 10 shows the thermal camera analysis in comparison to the finite element method results. Thermal camera images have a similar distribution to computational ones but are a noticeable accumulation of temperature in the walls. This fact can be explained by the attempt of the heat to get out of the sample and consequently accumulate at the border of the block and in the insulating wall.
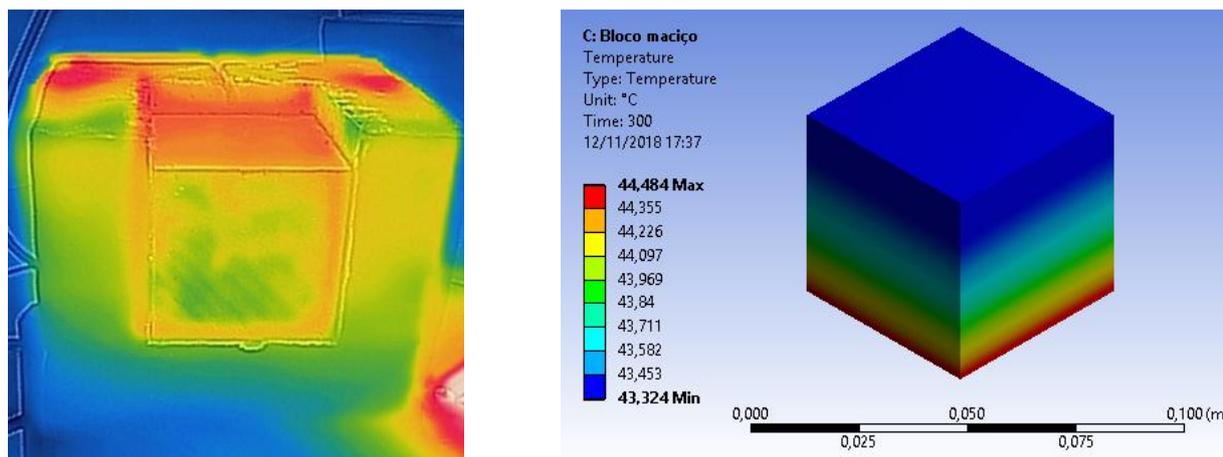

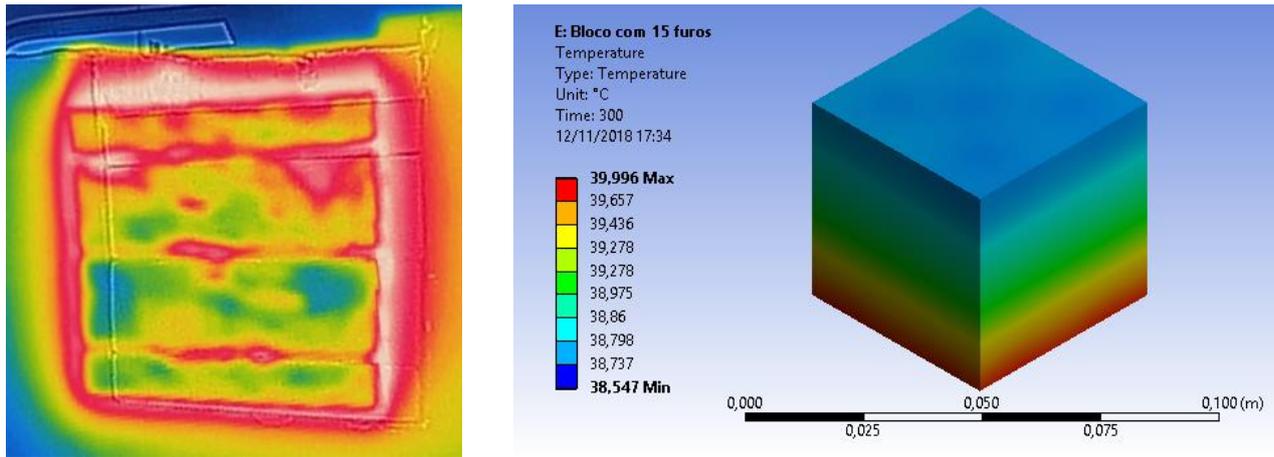Figure 7. Thermal camera and computational – Sample 1.

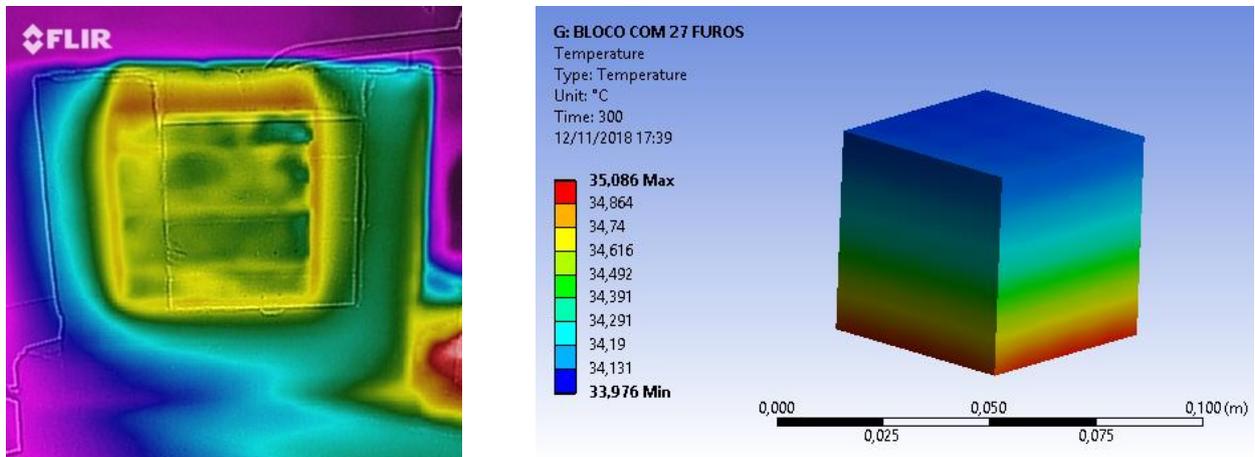Figure 8. Thermal camera and computational – Sample 2.

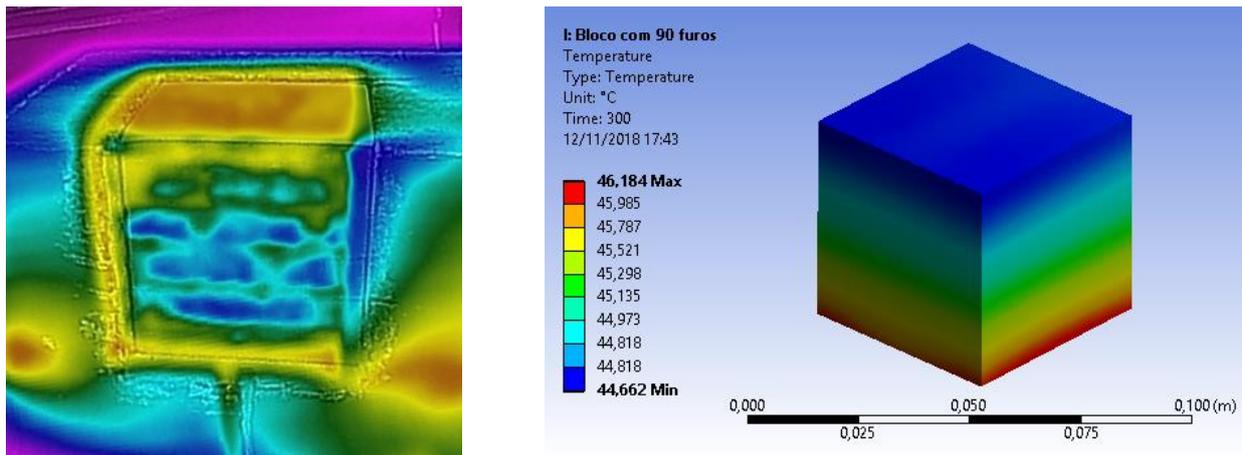Figure 9. Thermal camera and computational – Sample 3.

Figure 10. Thermal camera and computational – Sample 4.

Figure 11 shows the average founded through an experimental test and numerical procedures. The experimental test results were good, although due to the lack of control over the boundary conditions in the room where the experimental tests were performed, the results did not match exactly with computacional results data. All the specimens showed different temperatures and were noticed a considerable range of 8,5°C between the specimen that less dissipated heat and the more dissipate heat.

The linearity data the graph represents the numerical data test, and the linearity can be explained by the chosen boundary conditions, air convection and room temperature, being ideal and constant, samples showed the same distribution among the one that most dissipated the thermal energy and the one that dissipated least, that is, the sample with 90 insertions was the one that got the highest temperature in its analysis face while the sample with 27 insertions was the one that presented it lower temperature on the same face. The difference between the two samples was 10.6°C.
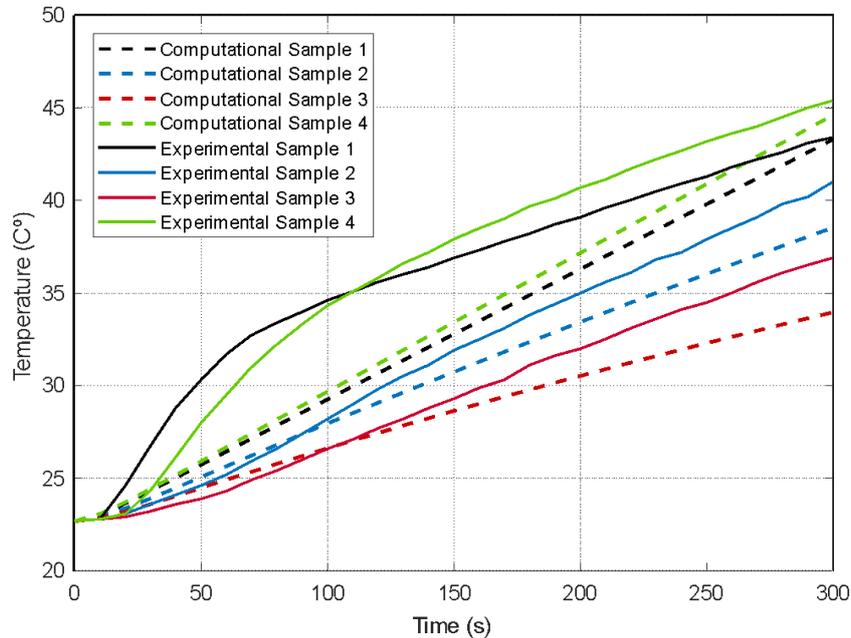

Figure 11. Experimental and Computational results.

It is possible to notice that in the first seconds of the experimental analysis, the thermal inertia in sample 1. When the sample comes into contact with the hot plate there is a certain delay in the absorption of heat which is immediately compensated by a high thermal gain. In the end, the temperature increase and the experimental data become almost linear to the computational test. Experimental sample 1 final temperature was 43,4 °C with a difference between the computational one of 0,1 °C. In sample 2 it is noticed that the specimen has little temperature gain in the first minute. The air inserted in the inclusions presents a heat transfer coefficient smaller than aluminum, making the heat look for a massive way to propagate in the specimen. The final temperature was 41 °C in the experimental and 38,6 °C in the numerical.

Sample 3 has a similar behavior when compared with sample 2. Due to the air inclusion distributed linearly in sample 3, the heat tends to search for a massive area to get to the surface with lower temperature however these areas without air insertion are smaller, there not so much heat dissipation. The final temperature was 36,9 °C in the experimental and 34 °C in the computational test.

The behavior of sample 4 was quite similar to sample 1 analysis, due to the sample 4 air inclusions being facing the end of the specimen. The massive middle directed the heat to the surface and making the sample presents heat transfer higher them the other samples. The final temperature was 45,5 °C in the experimental and 44,6 °C in the computational test.

4. CONCLUSION

The thermal behavior of an aluminum block with air inclusions has a complicated interpretation when it is not clear what geometry can influence. In this study, it was confirmed that the distribution of air inclusions has a great influence on the heat transfer problem since the final temperatures were different in all specimens tested.

In the computational and experimental test, it was possible to see that the greater is the number of air inclusions in the alloy, the less conductive becomes the composite material. Conversely, in the study between two samples with the same amount of air inside the specimen structure, but with different size and distribution, it was obtained a divergent result, being the sample 4 with 90 inclusions of 8 mm, had higher temperature even that the massive specimen. This phenomenon occurs because the heat tries to find the easiest way to get through with the air inclusion distributed on the sides of the sample heat pass through the middle (massive way), resulting in the higher temperature gradient between all tested geometries.

The temperature values obtained with ANSYS proved to be close to those of the physical model. The difference in values was caused by the lack of control of the room conditions and inaccuracy of measurement instruments used in the experimental test. For the reason of plate area being larger than the specimen area, the test results did not have a good agreement, due to a thermal loss by radiation and convection, unlike the computational test where the specimen received the total thermal energy on the specimen face. The control of the experimental procedure was not within the knowledge to the authors, such as airspeed and humidity. Such parameters are constant in the computer simulation, is provided as input data for the boundary conditions of the problem in question.

5. ACKNOWLEDGEMENTS

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