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Numerical Simulation of Transient Heat Transfer During Welding Process.

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ABSTRACT

In the development of a new compressor, the study of welding process becomes a very important analysis. There is a special interest to know the temperatures of the components inside the compressor that cannot be exposed to high values while it is being welded. This work presents a numerical simulation of the heat transfer on the compressor during the welding process. A number of welding variables was initially studied with a lumped parameter model. After that, the best welding process was detailed analyzed using a numerical solution of a three dimensional transient model. All the monitored temperatures during the simulation were very close to the temperatures measured with thermocouples during the experimental analyzes.

1. INTRODUCTION

Throughout the development of new projects, computational simulations are presented as important analysis tools, because they can estimate how the final products will react during their operation or manufacturing process. In the recent years, the interest about the numeric simulation problems that involve welding has grown; they are utilized to simulate process (Bourqui *et al.*, 2002), thermal (Zhu and Chao, 2004) and mechanical (Labeas *et al.*, 2005) problems.

In this work, laser and plasma welding processes were simulated and the housing temperature behavior was analyzed. The initial issue was to know which of these two welding processes would be the most appropriate, considering that some components inside the compressor cannot be exposed to temperatures greater than 120°C (248°F). Welding processes, laser and plasma, promote the joining by localized melting of the parts at the welding joint region. The problem related to the latent heat is incorporated directly in the specific heat of material, which is artificially raised through the interval where occur the phase change (Capriccioli and Frosi, 2009), (Real and Oliveira, 2003), (Yaghi *et al.*, 2008). To compare the 3D numerical simulation and a method of lumped mass solutions, an energy balance was done around a point with the same mass of the cylinder and the average temperature from the housing through the 3D simulation was caught.

After this analysis, the laser welding process, which is the most suitable process for the purpose, was detailed analyzed using a three dimensional transient model. To monitor the temperatures inside the compressor through the simulation, two points in the shell and four at inside components were utilized. During the experimental tests,

thermocouples were installed in the same points and the monitored temperatures were very close, proving the efficiency from the simulation to predict the real behavior of the welding process.

2. WELDING ANALYSIS AND CONSIDERATIONS

2.1 Simulation process

With the intention to simulate the welding process, the weld was defined as a heat flux in a squared area with dimensions of 3x3 [mm]. Initially was welded one side of the body and afterwards the other side, referring to the two circular ends of the housing. To analyze the housing that will be welded, a cylindrical geometry with external diameter of 50 [mm], internal diameter of 44 [mm] and length of 112 [mm] were developed, since that these are the real dimensions of the compressor body. The simulation done was 3D and transient. Figure below shows the heat flux related to welding process and the cylinder that represents the housing from the compressor.

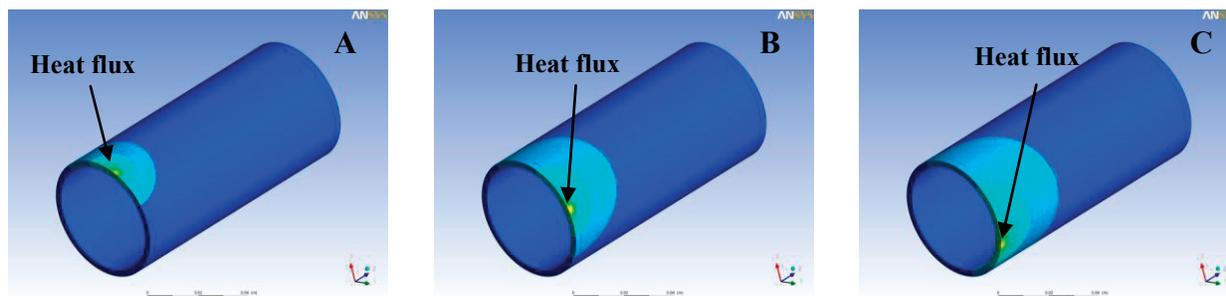


Figure 01 – Welding simulation process at (a) 5 seconds, (b) 10 seconds and (c) 15 seconds.

The material used to manufacture the body is aluminum and the properties utilized in the analysis were those presented in Ansys library:

- Density: 2702 kg/m³;
- Specific heat: 903 J/kg K;
- Thermal conductivity coefficient: 237 W/m K.

The initial and boundary conditions are:

- Body initial temperature: 25°C;
- Environment temperature: 25°C;
- Side and internal walls: Adiabatic walls;
- External wall: Convection heat transfer with heat transfer coefficient equal to 5 [W/m²K].

As described before, two different welding processes were analyzed: one uses the plasma and another uses the laser. The important parameters of the welding process are: heat input and welding velocity, whose values in processes are presented below at table 01. These values are provided by the supplier machine.

Table 01 - Parameters for each welding process.

Welding Process	Heat Input [W]	Welding Velocity [mm/s]
Plasma	720	3.3
Laser	134	1.0

This value of heat input is already the total power gave by the laser welding machine multiplied by the absorption that is the same as:

$$\text{Heat input} = \text{Power} \times \text{Absorption} = \text{Power} \times (1 - \text{Reflectivity}) \quad (1)$$

The values for reflectivity for some materials are presented at figure 02.

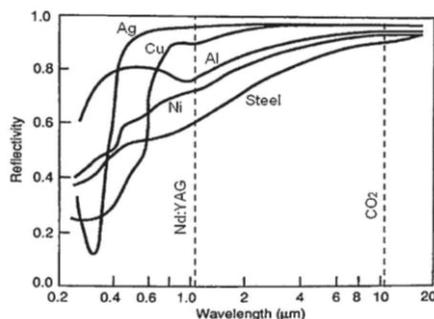


Figure 02 – Reflectivity of laser radiation for different materials.

The mathematical model of heat transfer is ruled by (Radaj, 1992):

$$\rho(T) \times C_p(T) \times \frac{\partial T(x, y, z, t)}{\partial t} + k(T) \times A \times \nabla^2 T(x, y, z, t) = Q(x, y, z, t) \quad (2)$$

where k is thermal conductivity, ρ density, C_p specific heat, $T(x, y, z, t)$ temperature distribution, A area from transversal section, $Q(x, y, z, t)$ is the heat generation per unit volume and t time. The temperature values that satisfy this equation into a domain should satisfy the boundary conditions imposed by problem. The heat transfer by convection is described by equation:

$$q_c = h_c \times A \times (T_c - T_\infty) \quad (3)$$

where q_c is the heat transfer by convection, h_c is the convective coefficient, T_c is the superficial body temperature and T_∞ is the environment temperature.

After this first analysis, the temperatures found through the simulation were higher than the melting temperature, so the representation of the latent heat is essential; otherwise the temperatures in simulation would be greater than the real one find when the welding would be done. With this proposal and knowing that the latent heat (heat necessary for phase change) from aluminum is 930.000 [J/kg] and knowing that the material has the melt process as a isothermal, was necessary to introduce a fictional temperature interval and a C_p equivalent value to solve the problem.

The equations that rule the sensible heat transfer (simple heat change) and the heat latent transfer (phase change) were equaled:

$$m \times C_{peq} \times \Delta T = m \times L \quad (4)$$

where m is material mass, ΔT fictional temperature difference and L latent heat. The variation of C_p is shown at figure 03. It was analyzed two different temperatures both were compared with constant specific heat coefficient.

By the other side, there is a possibility that the temperature of one node advance more than the “fictional” temperature interval at a given time step, this is possible to see in the figure 04, using smaller time steps the temperature advanced inside the “fictional” temperature interval (curve 01) and using larger time step it did not (curve 02). To verify the influence of this condition, two different time steps, “period/50” and “period/500” and also two different fictional temperatures (50°C and 100°C) were used. That is also a care to prevent numerical errors. Therefore, the period is equals to three times the welding time, where the welding time is the time to weld each

body's side. The period value took as three times was done to analyze the temperature history profile field after the process welding is finalized.

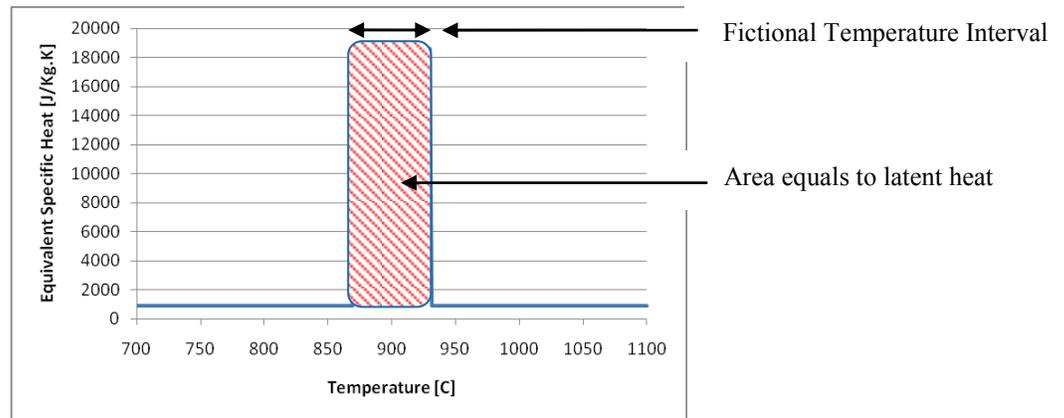


Figure 03 – C_p variation with 50K of temperature difference.

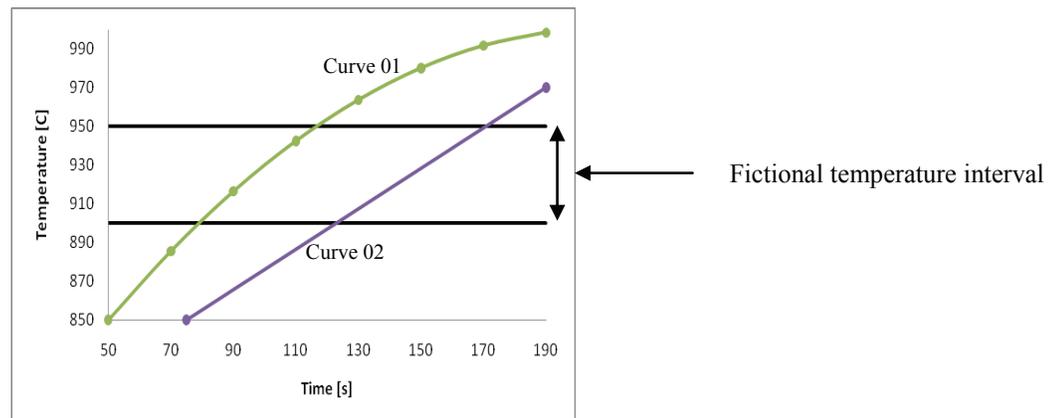


Figure 04 – Comparison from node advance temperature.

To validate the implementation done, a control volume were defined around the compressor body and an energy balance were done.

$$E_{in} - E_{out} = \Delta E_{st} \quad (5)$$

where E_{in} is the incoming energy and in this case, the welding potency. E_{out} is the out coming energy that is represented by the convection heat transfer and ΔE_{st} is the energy stored by the studied material. Using an explicit scheme, equation (5) could be rewritten as:

$$q_{weld} - h \times A \times (T_t - T_\infty) = m \times C_p \times \frac{T_{t+1} + T_t}{\Delta t} \quad (6)$$

Solving this equation, considering the initial conditions as the same as the implemented to the cylinder case welded with plasma process, the time step determined by the welding period divided into 500 parts, the temperature values will be solved for each time step. However, these calculated temperature values were considered constant for all body. So to compare lumped mass method and the 3D results, the average temperature value from the compressor body should be calculated through the simulation.

After the simulation, the analysis presented the behavior of temperatures during the studied processes, and the laser represents the most proper solution for the welding process purpose. But also the energy gave to the process is too high, so other process conditions were discussed and finally we allied the better conditions for the initial purpose and the conditions provided by the machine supplier. Table 02 shows the values for these parameters.

Table 02 – Better parameters found for laser welding process.

Laser Welding Parameters	
Welding Velocity [mm/s]	3,7
Heat Input [W]	118

The compressor has different materials for its components, so new materials and their properties were introduced into Ansys library and were used through the welding simulation. These materials were described in the table below.

Table 03 – Materials from compressor components and their properties.

Material	310 Stainless Steel	AISI 4340 Steel	Aluminum A380	Aluminum 6351
Density [kg/m ³]	8030	7850	2760	2710
Specific heat [J/Kg.C]	502	475	983	890
Thermal Conductivity [W/m.K]	13,8	44,5	109	176

The initial and the boundary conditions for compressor housing and cylindrical model are the same, the only difference is that the heat transfer coefficient is now 20 [W/m².K] (Incropera and DeWitt,2002), this value is estimated because the laser welding process needs a flow of argon at a rate of 7 [l/min]. It was unnecessary to account the variation of the specific heat due to melting as the temperature filed history was far below the melting temperature.

2.2 Experimental analysis

The laser beam welding has peculiar characteristics: high power density, which gives deep penetration with low heat input; clean welding, without splatter and high welding velocity (Balasubramanian *et al.*, 2008). The experimental analysis was made with a Nd:YAG laser machine (American Welding Society, 1991). The process consists of welding the covers to the shell of the compressor, with a power of 118 [W] and a welding velocity of 3,7 [m/s]. There are thermocouples inside the compressor that measure the temperature of the internal components. Figure 05 shows the instrumented compressor being welded.

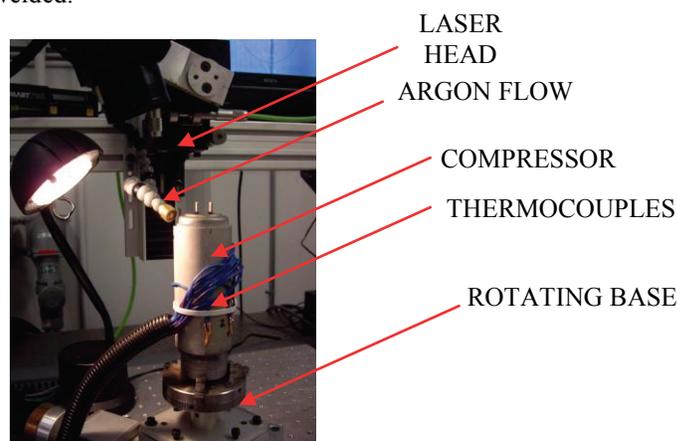


Figure 05 – Instrumented compressor being welded.

3. RESULTS AND DISCUSSION

Because the initial analysis idea is to know the highest temperature inside the compressor, temperatures values were monitored through the simulation process and the results were presented at figures 06, 07 and 08, being that the first graphic represents the plasma welding process and the second and the third the laser welding process. The table 04 indicates the cases presented and their characteristics.

Table 04 – Analyzed cases during the simulation.

Analyzed Cases				
	Case 1	Case 2	Case 3	Case 4
Fictional Temperature Interval	50	50	100	Constant Cp
Time step	Period/50	Period/500	Period/50	Period/50

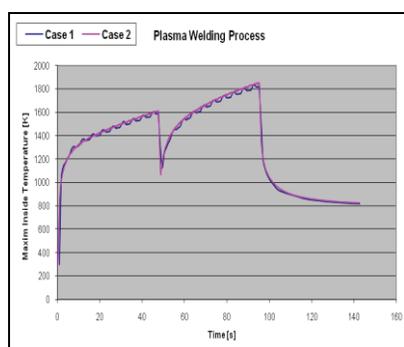


Figure 06 – Maximum inside temperatures through plasma welding process.



Figure 07 – Maximum inside temperatures through laser welding process.

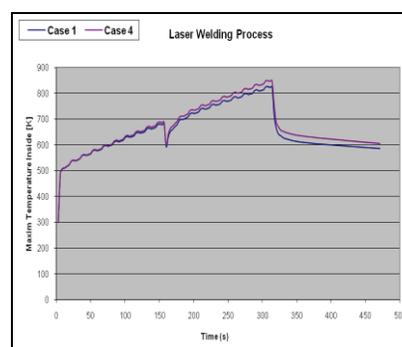


Figure 08 – Maximum inside temperatures through laser welding process.

Analyzing the two first graphics is possible to see that the variation from the maximum inside temperature was not significant when comparing the fictitious temperature difference of 50 and 100 °C and the difference of time step. But it is possible to note a curve variation when we're relating C_p variable and constant (Figure 08). As expected, the variable C_p curve came under the variable curve. It happens because a portion of the heat is being consumed to change the material's phase when C_p is considered variable. Another thing that is important to perceive is the dip in the temperatures during the welding process. It is a result of switching from one top to the other.

The highest inside temperature values are described at table 05. After the simulation was done, the 3D simulation and the lumped mass method results should be compared (Figure 09). Analyzing the graphic, it is easy to see that the curve traced above the points from average body compressor temperature during the simulation and the curve traced above the points from temperature calculated through the analytical problem were very close, what confirms the validity of the simulation.

Table 05 – Maximum inside temperatures for analyzed cases.

	Plasma	Laser
	Maximum Temperature [K]	Maximum Temperature [K]
Case A	1828	826
Case B	1856	827
Case C	1837	826
Case D	1858	827
Case E	1958	849
Case F	1969	853

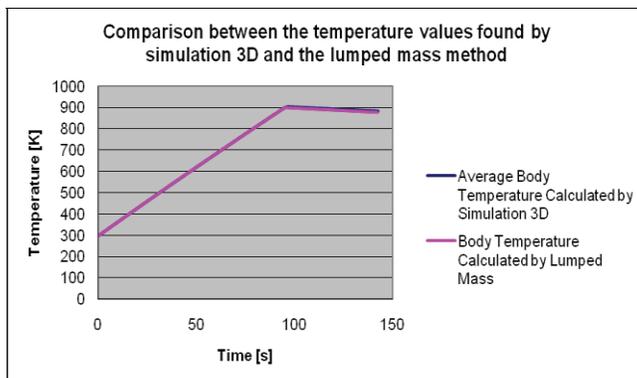


Figure 09 – Lumped mass method and simulation comparison.

The comparison between experimental analysis and simulated test during laser welding are presented in the figures below. The points that are shown at the graphics are illustrated at figure 16; this is a lateral view from the compressor and the points are pointed out the compressor, but at real they're inside of it.

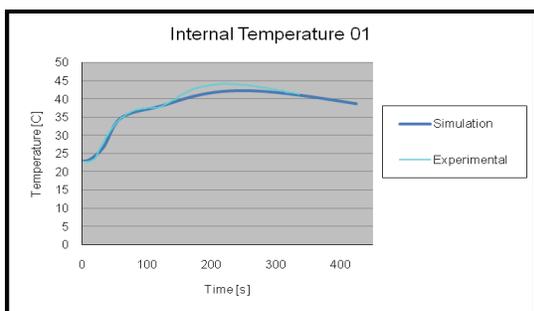


Figure 10 – Internal Temperature 01.

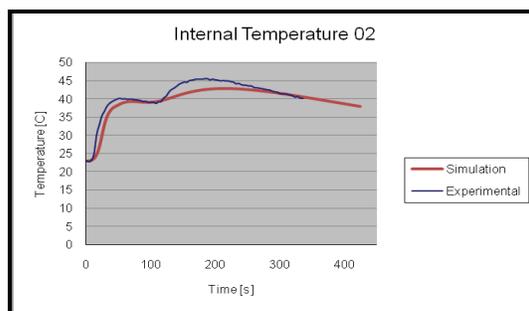


Figure 11 – Internal Temperature 02.

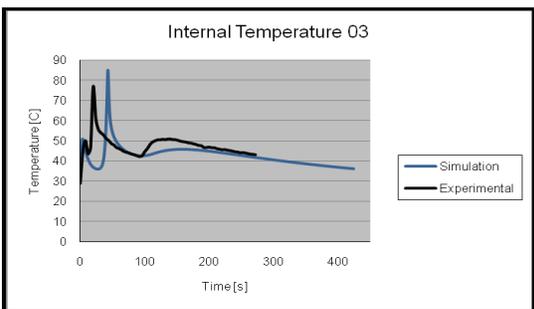


Figure 12 – Internal Temperature 03.

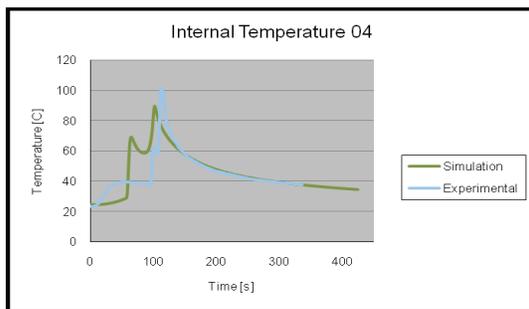


Figure 13 – Internal Temperature 04.

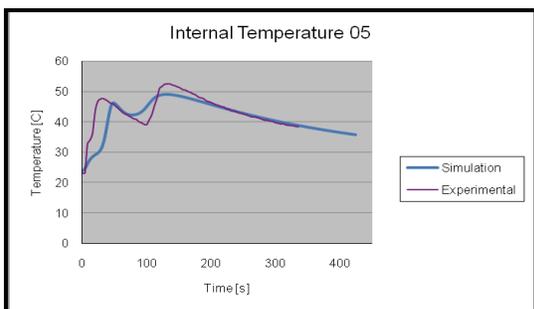


Figure 14 – Internal Temperature 05

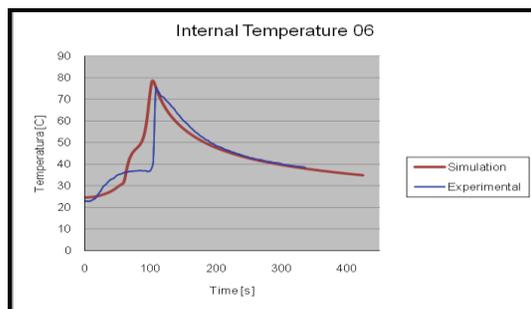


Figure 15 – Internal Temperature 06

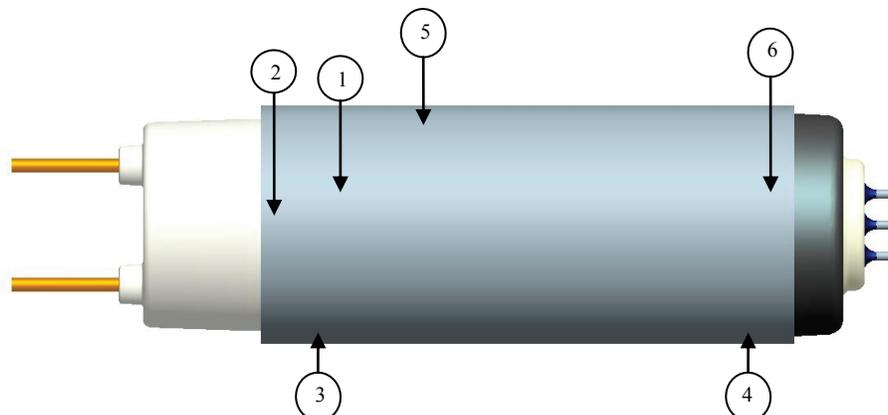


Figure 16 – Illustration of real compressor showing the analyzed points.

The graphics show that the numerical experiment can represent the real temperatures during the welding process with great accuracy and can be used in the initial development of welding process applied to compressors.

4. CONCLUSION

The comparison between the numerical simulations results and the experimental data obtained demonstrates that the method to determinate housing and internal components temperatures of the compressor during the sealing weld is effective. In this way, this method can be used in future developments to choose the process and the welding parameters that meet the thermal requirements of the project. It's possible to reduce the development time of the welding process for new products.

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