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# Mathematical analysis for the selection of the heating equipment of the hot forming stamping

# Análisis matemático para la selección del equipo de calentamiento del proceso de estampado en caliente

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## Abstract

This article shows the mathematical development to determine the length and cycle time of a furnace that is used for heating parts in the hot forming process. The input parameters, the required production capacity and the temperature to reach the austenite phase in the material were used. For the mathematical process, it was necessary to know the stages for the process, considering that there are two methods: the direct and indirect process. Subsequently, the number of annual pieces that should be produced per year was determined, thereby being able to conclude the cycle time that should be estimated for the furnace; Likewise, some thermal parameters that the oven must have were known, such as the internal temperature, which helped to know its length, in order to meet the demands of the production volume. This work aims to present alternatives to the industries dedicated to the stamping process, specifically hot forming stamping, based on the analysis of the selection of the heating equipment, based on the production needs.

**Stamping, Development, Mathematical**

## Resumen

El presente artículo muestra el desarrollo matemático llevado a cabo para determinar la longitud y el tiempo ciclo de un horno que es usado para el calentamiento de piezas que son sometidas a un proceso de estampado en caliente. Como parámetros de entrada se usó la capacidad de producción requerida y la temperatura para alcanzar la fase de austenita en el material. Para llevar a cabo el desarrollo matemático, fue necesario conocer las etapas del proceso, considerando que existen dos métodos para realizarlo, como son: el proceso directo e indirecto. Posteriormente se determinó la cantidad de piezas anuales que se deberían de producir por año, con ello poder concluir el tiempo ciclo que se debe estimar para el horno; también se conocieron algunos parámetros térmicos que debe poseer el horno, como son la temperatura interna, la cual ayudó a conocer la longitud del mismo, con la finalidad de que cumpla con las exigencias del volumen de producción. Con este trabajo se pretende ampliar el panorama a las industrias dedicadas al proceso de estampado, específicamente del estampado en caliente, lo anterior basado en el análisis de la selección del equipo de calentamiento, a partir de las necesidades de producción.

**Estampado, Desarrollo, Matemático**

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## 1. Introduction

Technological progress within the production sector has led industries to have equipment with greater capacities to carry out the tasks entrusted to them.

Within the automotive sector is the forming of parts, in which there are a series of equipment with which they work, among which are the heating furnaces.

Raising the temperature of the part to be worked on is of vital importance, as it depends on it to have the right microstructures, and consequently, to be able to have the mechanical properties that are sought in the part.

The main objective of the hot stamping process is to develop parts with high impact resistance (up to 1600MPa), but with very thin part thicknesses (up to 2mm).

In this work, an analysis of the furnace capacity will be carried out, which must meet the production volume requirements set by the production sector.

The work is considered to be carried out through a sequence of steps, which will lead to fulfil the objective.

The article initially proposes a methodology based on the particular needs of the project. Subsequently, in the development, the stages of hot stamping by the direct method and the indirect method are described. Within this same section, the chemical composition is shown, as well as some of the thermal properties of the material to be heated. The behaviour of the emissivity property of the material with respect to temperature is also reviewed in order to determine an adequate heating time, considering equations that involve the production volume; likewise, as a viable alternative to determine the heating time, the heating speed of the part will be known.

In the results section, the cycle time of the furnace can be observed, as well as the length of this (furnace), which is the end point of the project. Finally, there will be a conclusion of the work, where it will be reviewed if the objective was fulfilled, and consequently, the improvements that can be carried out will be commented.

## Methodology to be developed

The success or failure of a project is based on the adequate design of a methodology to be followed, which must be adjusted to the characteristics and needs of the project, in order to achieve the proposed goal. The methodology carried out in this project is shown in Figure 1, in which it can be seen that the objective of the project was considered as important points, as well as the estimated production volumes over the course of a year.

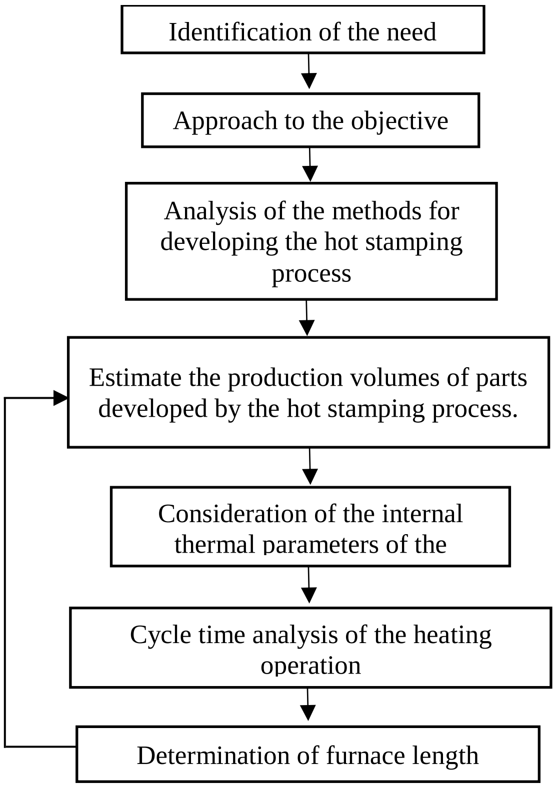

**Figure 1** Methodology
*Source: Own Elaboration*

## Development

## Consideration of the analysis of the study

Before starting the analysis and development of the process, it is important to comment that the study carried out in this work only contemplates the phenomenon of heat transfer by radiation. In studies carried out on this type of furnace, the 3 types of heat transfer mechanisms were considered: conduction, convection and radiation, at different temperatures between the furnace and the workpiece, with radiation as the dominant heat transfer mechanism (Dvorak, Tawk and Vít, 2016).

## Methods for carrying out the hot stamping process

To further understand the importance of the furnace as a necessary element in the part forming process, it is necessary to understand the hot stamping methodology.

The stamping process involves a sequence of steps in which small parts, known as sheets, are formed. This process uses dies, presses, among others, as common elements.

Unlike conventional stamping, the hot stamping process uses heat as a support to obtain the mechanical properties required by the elements that are subjected to high impacts, high stresses, among others.

The hot stamping process can be carried out in two different ways:

## Direct method

In the direct method of the Hot Forming Stamping (HFS) process (Figure 2), the sheet is brought to a temperature between 900°C and 950°C to obtain an austenite microstructure, then transferred to the die where the form is made, followed by cooling through a heat transfer unit. At temperatures above 700°C, the material can be handled excellently, so that it can take the shape that the die has. The stamping is carried out on the foil and cooled under pressure for a certain time, according to the thickness of the foil. During this period the stamped part is cooled at speeds ranging from 50 to 100 °C/s by circulating water, thus obtaining the ideal microstructure.

Finally, the stamped part leaves the hot stamping line at around 150 °C and with it excellent mechanical properties: tensile strength of 1,400 to 1,600 MPa (around 200 to 230 KSI), as well as a yield strength between 1,000 and 1,200 MPa (around 145 to 175 KSI).

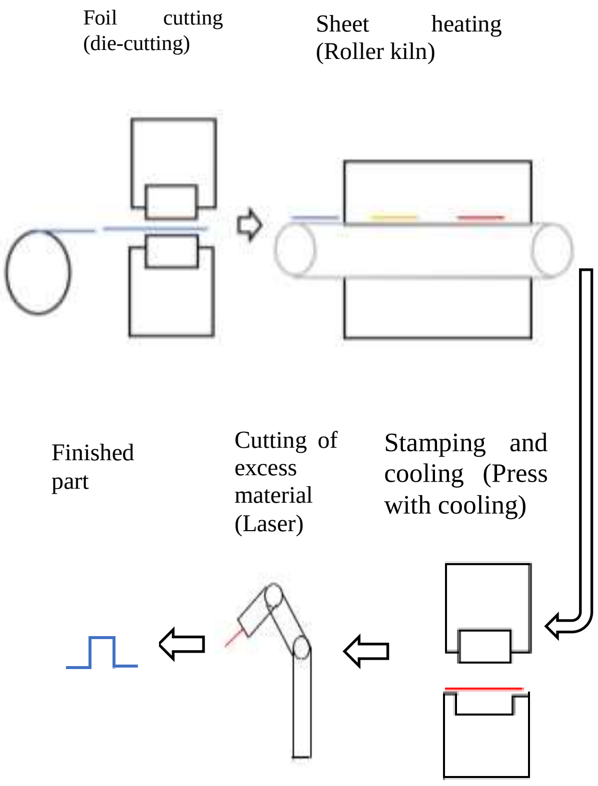

**Figure 2** Direct method of the HFS process
*Source: Own Elaboration*

## Indirect method

Unlike the direct process, the indirect hot stamping process has an additional operation called preforming (no heat is added in this operation), in which 90% to 95% of the final shape is formed. The preformed part is then heated to austenitising temperature (approximately 950 °C) in a continuous furnace, and the final shape is then made, in addition to cooling inside the press (Figure 3).

Having known the hot stamping process by the direct and indirect methods, we proceeded to know the type of steel that can be worked by this process, knowing that the sheet material must be a boron steel to work hot and thus be able to obtain the necessary properties.

The materials commonly used for the hot stamping process are boron steels, since, due to their mechanical properties, after hot stamping, they are positioned within the range of steels developed to meet the demands required by vehicle assemblers.

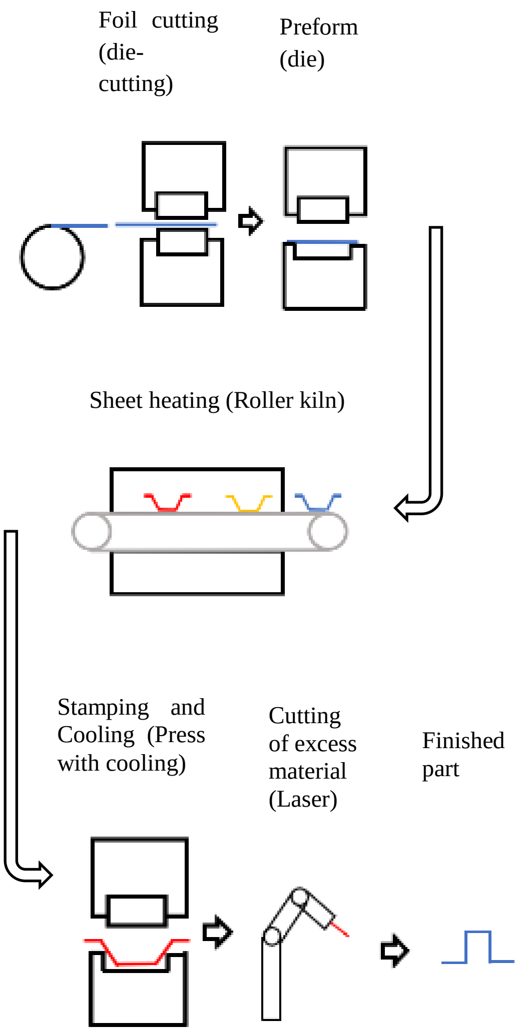

**Figure 3** Indirect method of the HFS process
*Source: Own Elaboration*

Table 1 shows the chemical composition of boron steels (Ganapathy et al., 2019), which are used for the hot stamping process, specifically refers to 22MnB5 steel.

| Component | % of composition |
|---|---:|
| C | 0.20 |
| Mn | 1.17 |
| Si | 0.25 |
| Cr | 0.20 |
| S | 0.002 |
| B | 0.0029 |
| Ti | 0.028 |
| Nb | 0.001 |
| Ni | 0.023 |

**Table 1** Chemical composition of boron steel
*Source: Own Elaboration*

The analysis of the heating time depends on the thermal properties of the material, among which are: density, heat capacity, thermal conductivity (Shapiro, 2009), which are shown in Table 2:

| Thermal property | Quantity |
|---|---|
| $\rho$,density $(kg/m^3)$ | 7830 |
| $C_p$,heat capacity $(J/kg * K)$ | 650 |
| $k$,thermal conductivity $(W/m * K)$ | 32 |
| λ,latent heat , $(kJ/kg)$ | 58.5 |

**Table 2** Thermal properties of boron steel
*Source: Own Elaboration*

During the hot forging process, the material undergoes microstructural changes, which are described below:

At the beginning of the process, the material has a ferritic-perlitic microstructure with a tensile strength of 600 MPa. It enters the furnace to be heated to a temperature between 900 °C and 950 °C, as a result of which the microstructure changes to austenite. It is then transferred to the press, where it reaches a temperature between 650 °C and 850 °C, the part is shaped and quenched in order to obtain a martensitic microstructure and a strength of 1600 MPa.

Figure 4 shows the microstructural changes during the hot stamping process, from the time it enters the furnace until it leaves the stamping station.

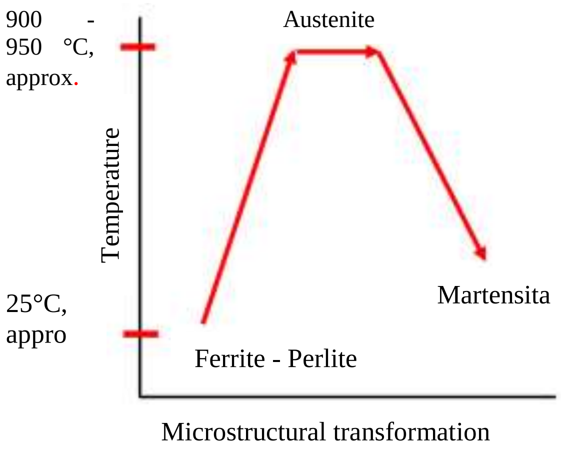

**Figure 4** Microstructural changes within the HFS process
*Source: Own Elaboration*

### 3.4 Heating-up time of the workpiece

The heating time plays an important role in the selection of the furnace, as the size required for the furnace depends to a large extent on this, as well as the production volume. Also, within the equations, the volume of the part being worked on is considered, so it is necessary to know its geometric dimensions.

The part that will be taken as a parameter is the lateral reinforcement of the vehicle, for which the sheet will be considered to be 1.4m long by 0.6m wide, as well as a thickness of 1.5mm (Figure 5):

**Figure 5** Dimensions of the working sheet
*Source: Own Elaboration*

For the determination of this time, some thermal parameters were considered, among which are: temperature inside the furnace, the temperature of the film and the emissivity (Dvorak, Tawk and Vít, 2016); the above data can be seen in Table 3.

| Temperature inside the oven | °C | 930 | 930 | 930 |
|---|---|---|---|---|
| Film temperature | °C | 25 | 600 | 900 |
| Emissivity | (1) | 0.38 | 0.11 | 0.54 |
| Convection heat transfer coefficient | (W $m^{-2}$ $K^{-1}$) | 9.50 | 5.60 | 4.10 |
| Radiation heat flux | (W $m^{-2}$) | 44.96 | 9.44 | 6.16 |
| Convection heat flux | (W $m^{-2}$) | 8.6 | 1.85 | 0.12 |

**Table 3** Chemical composition of boron steel
*Source: Own Elaboration*

As can be seen in Table 2, emissivity is a function of temperature, and therefore of time. It can also be seen that the heat flow by radiation is the parameter that has the greatest effect on the part to be heated, so the geometry that describes the behaviour of emissivity with respect to temperature was determined (Figure 6).

The geometrical locus shown in Figure 6 can be described in mathematical terms by Equation 1:

$$\varepsilon = 2.175x10^{-6}T^2 - 1.83x10^{-3}T + 0.424 \quad (1)$$

Where:

ε = Emissivity
T = Temperature in °C

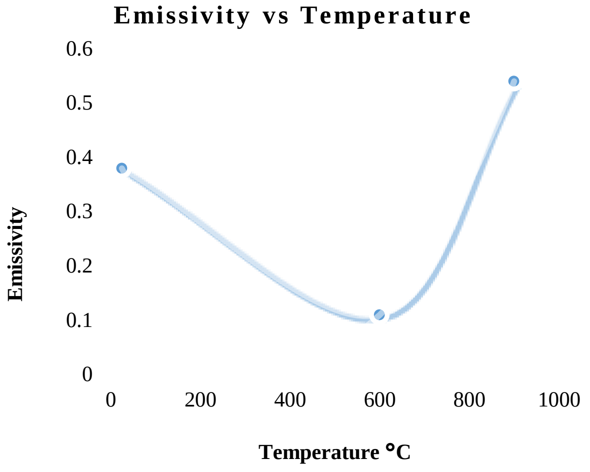

**Figure 6** Behaviour of emissivity vs temperature
*Source: Own Elaboration*

Equation 4 provided an approximation of the emissivities at different temperatures, with which it is possible to determine the total time the workpiece would spend in the furnace. Table 4 shows the emissivities inside the furnace at various temperatures:

| Temperature (°C) | Emissivity |
|---|---|
| 25 | 0.37961 |
| 100 | 0.26275 |
| 200 | 0.145 |
| 300 | 0.07075 |
| 400 | 0.04 |
| 500 | 0.05275 |
| 600 | 0.109 |
| 700 | 0.20875 |
| 800 | 0.352 |
| 900 | 0.53875 |

**Table 4** Emissivities at various temperatures
*Source: Own Elaboration*

Equation 2 (Incropera & Dewitt, 1999) was used to determine the heating time as a function of emissivity and temperatures:

$$\rho V c \frac{dT}{dt} = -\sigma \varepsilon A (T^4 - T_\infty^4) \quad (2)$$

Solving the differential equation between the limits (T=T_i @t=0) and (T=T @ t), we obtain Equation 3 (Incropera & Dewitt, 1999):

$$t = \frac{\rho V c}{4 A \sigma \varepsilon T_{alr}^3}\left[\ln\left|\frac{T_{alr}+T}{T_{alr}-T}\right| - \ln\left|\frac{T_{alr}+T_i}{T_{alr}-T_i}\right| + 2\left(\tan^{-1}\frac{T}{T_{alr}} - \tan^{-1}\frac{T_i}{T_{alr}}\right)\right] \quad (3)$$

Where:

V is the volume of the part to be heated.
A is the contact surface of the radiation phenomenon.
σ is the Stefan-Boltzman constant $(5.67x10^{-8}\ W/m^2 * K^2$
$T_{alr}$ is the temperature inside the furnace.
$T_i$ is the initial temperature of the workpiece to be heated.
T is the final temperature of the workpiece to be heated.

Equation 3 applies when the relationship given by equation 4 (Incropera & Dewitt, 1999) is fulfilled:

$$Bi = \frac{hL_c}{k} < 0.1 \tag{4}$$

Where:

$Bi$ is the Biot number which is a dimensionless quantity.
$h$ is the convective heat transfer coefficient.
$L_c$ is the critical length, in practical cases it is considered as the thickness.

Equation 5 (Incropera & Dewitt, 1999) is used to obtain Lc:

$$L_c \equiv {}^{V}/_{A} \tag{5}$$

On the other hand, it has been reviewed in some references that the heating time can be determined from controlled speeds, i.e. a heating speed of around 7.5 °C/s has been considered until a temperature of 750 °C is reached, then the speed is decreased from 7.5 °C/s to 1°C/s, this last speed is managed until 900°C, afterwards the temperature of 900°C is maintained for a lapse of 1 minute (Dvorak, Tawk and Vít, 2016), the above study was developed for 1.5mm thick sheets.

### 3.5 Production volume

To determine the number of parts per day, Equation 6 is used:

$$\text{No. of pcs/day} = \frac{{}^{\text{Pcs}}/_{year}}{{}^{\text{days}}/_{\text{year}}\text{ (working days)}} \tag{6}$$

Equation 7 was used to determine the number of parts per hour:

$$\text{No. of pcs/hour} = \frac{{}^{\text{Pcs}}/_{\text{day}}}{{}^{\text{hours}}/_{\text{day}}\text{(working days)}} \tag{7}$$

To determine the cycle time, Equation 8 was considered:

$$\text{t}_{\text{cicle}} = \frac{3600}{\text{No.of pcs/hour}} \tag{8}$$

Equation 9 describes the appropriate length for the furnace, which refers to the total distance the part will travel from entering at room temperature to leaving at austenitising temperature (Figure 7); this length is a function of the heating time, the cycle time and a term called "Llote", which is the length that a "group" of parts spans. The "Llote" can cover 1 part, 2 parts or more (Figure 8), as it will depend on the number of robots that are between the heating operation and the forming operation, as well as the cycle time that is handled in the latter.

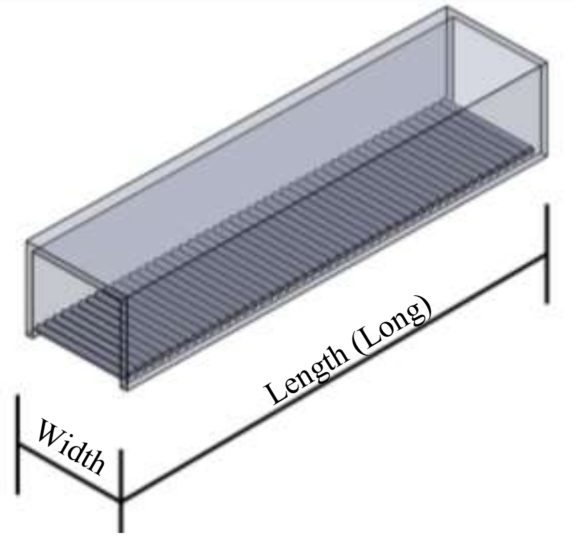

**Figure 7** Furnace length
*Source: Own Elaboration*

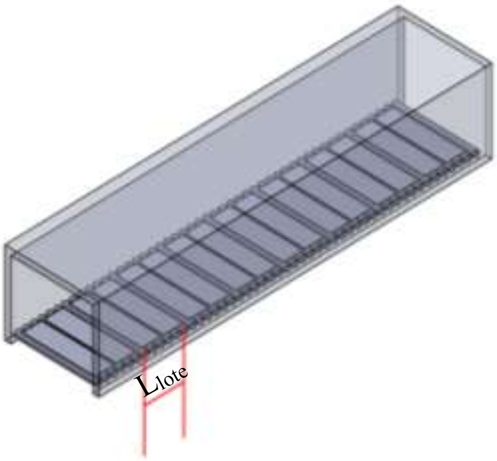

**Figure 8** Description of the term Llote
*Source: Own Elaboration*

$$\mathrm{L_{Oven}} = \frac{\mathrm{t_{heating}}}{\mathrm{t_{cicle}}}(\mathrm{L}_{lote}) \quad (9)$$

## 3. Results

Two methods were used to determine the heating time:

1. By taking into account the following properties of the material to be heated:

$\rho = 7830\ ^{\mathrm{Kg}}/_{\mathrm{m^3}}$

$\mathrm{C_p} = 650\ ^{\mathrm{J}}/_{\mathrm{Kg.K}}$

$\mathrm{V} = 1.26\mathrm{x}10^{-03}\mathrm{m}^3$

$\mathrm{A} = 0.84\mathrm{m}^2$

$\sigma = (5.67\mathrm{x}10^{-08})$

$\mathrm{T_{alr}} = 930°\mathrm{C}$

$\mathrm{T_i} = 25°\mathrm{C}$

$\mathrm{T} = 950°\mathrm{C}$

as well as the emissivities at the different temperatures, a total heating time of:

$t_{heating} = 345.66\ \mathrm{s}$

2. Considering the option in which the part is heated at 7°C/s until it reaches a temperature of 750°C, then heated at a rate of 1°C/s until it reaches 900°C, finally left at 900°C for one minute, we have a heating time:

$t_{eating} = 313.57\ \mathrm{s}$

In order to determine the cycle time of the production line, the following considerations were made:

For a total of 500,000 pcs/year.

This production volume is considering that the part being analysed is a lateral reinforcement, which is found on both sides of the vehicle.

Taking as a given that 240 days per year (working days) are worked, Equation 6 was used, so it was obtained that:

$\mathrm{No.\,of\,pcs/day} = 2083\ ^{\mathrm{Pcs}}/_{\mathrm{day}}$

To determine the number of parts per hour, Equation 7 was used, with the necessary data in addition to the consideration that in a working day 21 hours are worked (time at 100%) the following was obtained:

$\mathrm{No.\,of\,pcs/hour} = 100\ ^{\mathrm{Pcs}}/_{\mathrm{hour}}$

In order to determine the cycle time of the furnace, Equation 8 was considered, giving a cycle time equal to:

$t_{cicle} = 36\ ^{\mathrm{S}}/_{\mathrm{Pza}}$

Finally, the furnace length was obtained from Equation 9. Based on the two heating times determined, the cycle time and the area of the parts, as well as Llote = 1.4 m, the corresponding results are shown in table 5:

| $\mathbf{T_{Heating}}$ (s) | $\mathbf{L_{Oven}}$ (m) |
|---|---|
| 345.66 | 13.4 |
| 313.57 | 12.2 |

**Table 5** Furnace length in relation to heating time
*Source: Own Elaboration*

## 3. Conclusions

For practical purposes and quick and accurate results, the analysis can be considered only taking into account the controlled heating rate, since, due to the results obtained, the heating times are close.

Taking as a reference what exists commercially, the furnace should have a length of 15m and a width of 2m, with these dimensions, as well as an internal temperature that can reach at least 930°C, also taking into account the thermal conditions mentioned within the development, the production volume will be guaranteed. On the other hand, in order to contribute to the research on the analysis of the heating time, as well as to compare the results obtained in this work, an analysis of heating times can be proposed from the study of the microstructural changes as a function of time and temperature, considering the effect of the alloy components of the material.

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