

OPTIMIZATION OF THERMAL PROCESSING PARAMETERS OF A HIGH STRENGTH ALUMINUM ALLOY

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ABSTRACT

The work shows a calculation meant to optimize the thermal processing parameters (time and temperature) of a high strength aluminum alloy. The optimization calculation has been done by gradient method which involves multi-step (iteration) calculation of thermal processing parameters in which the values of the mechanical properties meet certain restrictions imposed. Identifying the most economic variants of heat treatment of those resulting from the application of gradient method was carried out by performing calculations of heat balance of the heat-treatment oven.

KEYWORDS: optimization, thermal processing, gradient method, parameters, heat balance

1. Introduction

Among the non-ferrous metals and alloys currently used in the top fields of engineering, aluminium and its alloys have the greatest weight due to the properties and characteristics of this metal and especially due to the classical hardening techniques of these alloys. Aluminium and its alloys occupy a foreground position in the category of metallic materials with great applications in engineering industry through a vast range of uses. The extensive use of aluminium alloys is due to its good mechanical properties which are obtained after thermal and/or thermo-mechanical processing.

By optimisation we understand the operation of studying a problem with a view to obtaining a result which, compared to other possible results at that moment, is the best, the most advisable and the one based on which a technical or economical decision can be made [1].

Optimizing thermal processing parameters allows for the selection of those existent parameters and conditions which will determine the best technico-economic performance of the process (choosing optimal parameters) [3, 5]. At the basis of any technological process, there is a mathematical model which has to express the respective process as precisely as possible. The mathematical model being the main element in running the process, its accurate design is of utmost importance for describing the process as accurately as possible, which means that there should be a high concordance between the

model and the process it describes [4, 5]. By determining some values of the independent variables we can determine the optimal solution so that the best value for the objective function (the function to be optimized) should be obtained [3]. According to each case, the optimum value of the objective function can mean its maximum or minimum value. The optimization methods are usually decreasing methods which express the minimum of a function U of n real variables which is called *aim* or *objective function*. In the case of optimizing the thermal processing parameters of the studied alloy, the objective function is represented by the energy consumption " $Q = f(t, \tau)$ ", taking into account some restrictions as far as the values of the analyzed mechanical properties are concerned.

2. The gradient method for optimizing the thermal treatment process of the studied alloy

The alloy studied belongs to the Al-Zn-Mg-Cu system and has the composition presented in Table 1.

The optimization calculation was achieved by the gradient method which implies the calculation of the thermal processing parameters in multiple situations (reiterations) which comply with certain conditions (restrictions) required.

The restrictions imposed refer to the values of the mechanical properties according to EN_485-2-2007 and are given in Table 2.

Table 1. Chemical composition of the alloy studied [mass %]

Element	Zn	Mg	Cu	Si	Fe	Pb	Cr	Mn	Al
AlZn6.5MgCu	6.5	2.70	1.80	0.15	0.20	0.02	0.20	0.15	rest

Table 2. Values of mechanical properties according to EN_485-2-2007 [11]

Rm, [MPa]	Rp0,2 [MPa]	A5 [%]	HB [MPa]
540	470	7	161

Besides the restrictions for the values of the mechanical properties, there are also some restrictions for the variation interval of the thermal processing parameters, the thermal treatment time and the thermal treatment temperature. They must have the following values:

$$120\text{ }^{\circ}\text{C} \leq t \leq 200\text{ }^{\circ}\text{C} \quad (1)$$

$$4\text{ hours} \leq \tau \leq 20\text{ hours} \quad (2)$$

The mechanical properties studied are:

- Mechanical resistance Rm, [Mpa];
- Yield resistance Rp0,2, [Mpa];
- Tensile elongation A5, [%];
- Brinell hardness HB.

The following mathematical equations are used for optimization, which are obtained after carrying out the mathematical modelling for each property analyzed.

$$Y_1 = 664.2589 - 1.1953 \cdot t + 7.6093 \cdot \tau - 0.0292 \cdot t \cdot \tau, \quad (3)$$

$$Y_2 = 627.371 - 1.262 \cdot t + 8.25 \cdot \tau - 0.032 \cdot t \cdot \tau, \quad (4)$$

$$Y_3 = 7.25 + 0.014 \cdot t - 0.1 \cdot \tau + 0.00031 \cdot t \cdot \tau, \quad (5)$$

$$Y_4 = 169.5357 - 0.2906 \cdot t + 4.687 \cdot \tau - 0.019 \cdot t \cdot \tau, \quad (6)$$

Where: $Y_1 = R_m$; $Y_2 = R_{p0,2}$; $Y_3 = A_5$; $Y_4 = HB$.

The gradient method is an iterative method which by multiple iterations facilitates finding the optimal complex of properties which comply with the restrictions simultaneously.

Partial derivatives of the function $Y_1(t, \tau)$ were calculated, (Y_1 is the main mechanical feature for which the maximum value is imposed in the given circumstances):

$$\frac{\partial Y_1}{\partial t} = -1.195 - 0.029 \cdot \tau \quad (7)$$

$$\frac{\partial Y_1}{\partial \tau} = 7.609 - 0.029 \cdot t \quad (8)$$

The gradient vector for Y_1 , which is the traction resistance, is:

$$\text{grad } Y_1 = (-1.1953 - 0.029 \cdot \tau; 7.609 - 0.029 \cdot t) \quad (9)$$

As starting point is chosen the point having the coordinates: $t_1 = 120\text{ }^{\circ}\text{C}$, $\tau_1 = 20\text{ hours}$, the point where the calculation of the minimum starts after the gradient direction.

Replacing the values of t_1 , τ_1 in the gradient expression of Y_1 we have: $\text{grad } Y_1(1) = (-1.079; -4.129)$.

The next stage is checking the boundary conditions in the initial point and it indicates that the properties of resistance as well as those of malleability are satisfied:

$$R_m(1) = 602.9289\text{ MPa};$$

$$R_c(1) = 564.131\text{ MPa};$$

$$HB(1) = 182.8037;$$

$$A_5(1) = 7.674\text{ } \%$$

In order to find the optimal point(s), we proceed as follows:

- the variation step $h = -0.4$ is chosen;
- a useful step for carrying out the transformation at the initial point is shown by a vector of the form [9]:

$$x_{i(N+1)} = x_{i,N} + h \cdot \frac{\partial Y_{i,N}}{\partial x_{i,N}}, \quad i = 1, 2, \dots, k \quad (10)$$

$$\text{the relationship: } x_{i(N+1)} = x_{i,N} + h \cdot \frac{\partial Y_{i,N}}{\partial x_{i,N}} \quad (11)$$

is calculated:

$i = 1, 2, \dots, k$, the coordinates of point 2, where x_i represents the heat treatment variables (t, τ):

$$t_2 = 120.71\text{ }^{\circ}\text{C}; \quad \tau_2 = 18.348\text{ ore};$$

- $R_m, R_{p0,2}, A_5$ and HB are calculated with the help of the mathematical models, and replacing t, τ with t_2, τ_2 we obtain:

$$R_m(2) = 619.056\text{ MPa};$$

$$R_c(2) = 572.081\text{ MPa};$$

$$A_5(2) = 7.011\text{ } \%$$

$$HB(2) = 180.148.$$

The restrictions are checked by iteration 2. t, τ calculated with the relation (11) are replaced in the relationship (10) and we obtain: $\text{grad } Y_1(2) = (-$

1.727; 4.108) which is important for calculating the variables t_3 , τ_3 at the next iteration.

Using the same calculation algorithm, which is edited in MATLAB program package, 40 iterations were solved for finding those values which comply with the conditions imposed by the restrictions.

The mechanical properties of the studied alloy, obtained by calculation by applying the gradient method for the 40 iterations, are represented in figures 1, 2, 3.

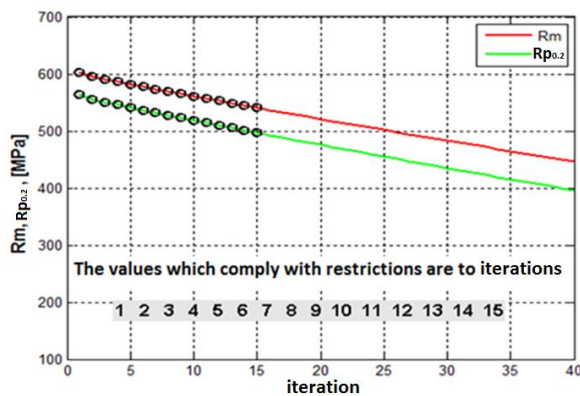


Fig. 1. Graphical representation of the values of mechanical and yield resistance obtained by calculation using the gradient method for the 40 iterations (the marked ones are those which comply with the imposed conditions)

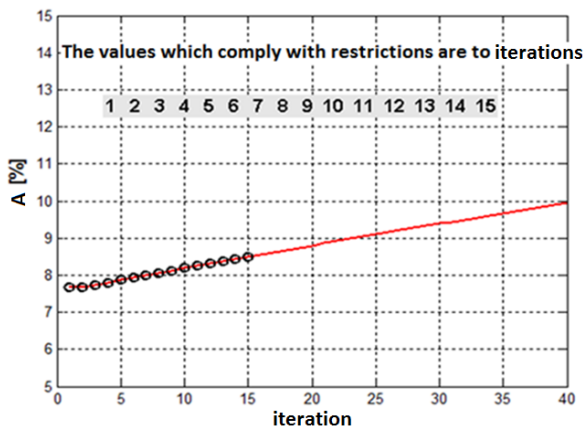


Fig. 2. Graphical representation of the values of tensile elongation obtained by calculation using the gradient method for the 40 iterations (the marked ones are those which comply with the imposed conditions)

For the iterations 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, it results from the calculation that the values of the mechanical properties studied as well as for the thermal treatment parameters t , τ are in accordance with the conditions imposed by the

restrictions (Table 1 and relationships 1 and 2). The values imposed for the properties by the Euro norm in use are reached for temperature values between 120 °C and 123.5 °C, while the time values range between 6 and 20 hours. In order to establish which of these values is optimum economically as well, the calculations for energy consumption were made.

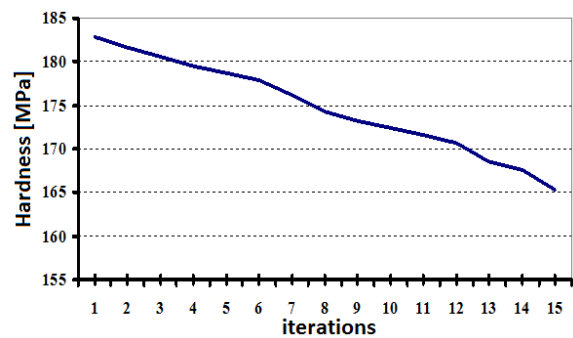


Fig. 3. Graphical representation of the values of the values of Brinell hardness obtained by calculation using the gradient method for the 15 iterations

3. Calculation of thermal energy consumption Q, [kWh]

In order to find out which of the 15 variants of thermal treatment is the optimum variant from the economic point of view, the calculation of the thermal energy consumption Q, [kWh] is made.

The calculation of the energy consumption under the form of heat (thermal energy) means the calculation of the total energy consumed at the thermal treatment oven where the artificial ageing is made according to the thermal processing variant and the relationship below:

$$Q_{total} = Q_{total \text{ oven}} \quad (12)$$

$Q_{total \text{ oven}}$ – the quantity of heat necessary for attaining and maintaining the treatment temperature over the whole period of the thermal treatment.

The oven on which the thermal treatment was carried out is an electrically heated oven with silit bars made of chamotte refractory brick, lined with mineral wool and having steel sheet on the outside. The energy consumed for performing the thermal heat treatment will be determined after carrying out the thermal balance of the treatment oven.

The energy consumption will be expressed by the quantity of heat necessary to maintain the treatment temperature while the thermal treatment is applied (Figure 4), according to the relationship:

$$Q_{total \text{ oven}} = Q_A + Q_B \quad (13)$$

Q_A – the quantity of heat consumed (energy) during heating the oven;
 Q_B – the quantity of heat consumed (energy) during maintaining the heat treatment temperature;

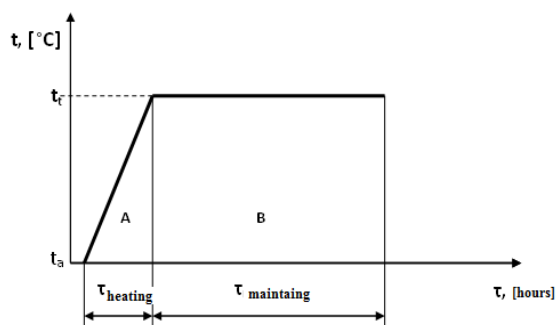


Fig. 4. Thermal treatment diagram

A – oven heating time from the ambient temperature to the thermal treatment temperature;
B – period of maintaining the heat treatment temperature inside the oven;
 τ_{heating} – oven heating time, [hours];
 $\tau_{\text{maintaining}}$ – time of maintaining the oven at the treatment temperature, [hours];
 t_a – ambient temperature, [°C];
 t_t – thermal treatment temperature, [°C].

The heat necessary to raise the temperature inside the oven from the ambient temperature to the heat treatment temperature is [37]:

$$Q_A = Q_{\text{ac sample A}} + Q_{\text{ac zid A}} + Q_{\text{pierd zid A}} \quad (14)$$

$Q_{\text{ac pies A}}$ – the heat accumulated in the pieces (samples) during the oven heating.

$$Q_{\text{ac sample A}} = m_{\text{sample}} \cdot c_{\text{sample}} \cdot \Delta t_1, \text{ [kJ]} \quad (15)$$

m_{sample} – sample mass, [kg];

$$\Delta t_1 = t_t - t_a, \text{ [°C]}$$

Δt_1 – the difference of temperature between the treatment temperature and the ambient temperature.

The samples (pieces) subject to artificial ageing heat treatment have the dimensions of 150x60x3 mm.

$$Q_{\text{ac zid A}} = (m_{\text{cs}} \cdot c_{\text{cs}} + m_{\text{vm}} \cdot c_{\text{vm}} + m_{\text{t}} \cdot c_{\text{t}}) \cdot \Delta t_1, \text{ [8, 9], [kJ]}, \quad (16)$$

$Q_{\text{ac zidarie A}}$ – the heat accumulated in the oven walls during heating;

c_{cs} – specific heat of the chamotte brick;

c_{vm} – specific heat of the mineral fibre;

c_{t} – specific heat of the steel sheet;

m_{cs} – mass of the oven chamotte refractory brick;

m_{vm} – mass of the mineral fibre used for oven covering;

m_{t} – mass of the steel sheet used for oven coating;

$$m_{\text{cs}} = V_{\text{cs}} \cdot \rho_{\text{cs}};$$

V_{cs} – volume of the chamotte refractory brick used to build the oven;

ρ_{cs} – density of the chamotte refractory brick;

$Q_{\text{pierd zidarie A}}$ – the heat lost through the oven walls during heating which is calculated using the heat flow, Φ_A ;

$$Q_{\text{pierd zidarie A}} = \Phi_A \cdot \tau_A, \text{ [Wh]} \quad (17)$$

τ_A – heating time for the inside of the oven, [h];

Φ_A – the heat flow during the heating period A

is:

$$\Phi_A = k_1 \cdot S \cdot \Delta t_2, \text{ [W]} \quad (18)$$

$$\Delta t_2 = t_m - t_a, \text{ [°C]}$$

Δt_2 – difference of temperature between the average temperature and the ambient temperature [37, 38].

$$\Phi_A = \Phi_{\text{oriz A}} + \Phi_{\text{vert A}} \text{ [37], [W]} \quad (19)$$

$\Phi_{\text{oriz A}}$ – the heat flow through the horizontal walls of the oven during heating;

$\Phi_{\text{vert A}}$ – the heat flow through the vertical walls of the oven during heating;

$$\Phi_{\text{oriz A}} = k_{\text{oriz}} \cdot 2 \cdot S_{\text{oriz}} \cdot \Delta t_2 \text{ [37, 38] [W]} \quad (20)$$

k_{oriz} – global coefficient of heat transfer through the horizontal walls of the oven during oven heating up to the thermal treatment temperature;

S_{oriz} – surface of a single horizontal wall of the oven;

$$\Phi_{\text{vert A}} = k_{\text{vert}} \cdot 2 \cdot S_{\text{vert}} \cdot \Delta t_2 \text{ [W], [8]} \quad (21)$$

k_{vert} – global coefficient of heat transfer through the vertical walls of the oven during its heating up to the thermal treatment temperature;

$$S_{\text{vert}} = S_{\text{vert 1}} + S_{\text{vert 2}} \quad (22)$$

S_{vert} – surface of all vertical walls of the oven;

Q_B , the heat necessary to maintain the samples inside the oven at the heat treatment temperature, equals the heat lost through the oven walls during this whole period.

$$Q_B = Q_{\text{pierdere zidarie B}}, \text{ [kJ]} \quad (23)$$

This can be expressed using the heat flow Φ_B :

$$\Phi_B = k_2 \cdot S \cdot \Delta t_1 \text{ [W], [8]} \quad (24)$$

Φ_B – heat flow during maintaining the samples at the thermal treatment temperature;

$$\Phi_B = \Phi_{\text{orizB}} + \Phi_{\text{vertB}} \text{ [W], [8];}$$

Φ_{orizB} – heat flow through the horizontal walls of the oven during maintaining the samples at the thermal treatment temperature;

$$\Phi_{\text{orizB}} = k_2 \cdot 2 \cdot S_{\text{oriz}} \cdot \Delta t_1, \text{ [W], [8]} \quad (25)$$

Φ_{vertB} – heat flow through the vertical walls of the oven during maintaining the samples at the thermal treatment temperature;

$$\Phi_{\text{vertB}} = k_2 \cdot S_{\text{vert}} \cdot \Delta t_1 \text{ [W], [37]} \quad (26)$$

$$k_2 = \frac{1}{\frac{\delta_1}{\lambda_1} + \frac{\delta_2}{\lambda_2} + \frac{\delta_3}{\lambda_3} + \frac{1}{\alpha_2}} \text{ [W/m}^2 \cdot \text{K], [8]} \quad (27)$$

K_2 – global coefficient of heat transfer during maintaining the oven at the thermal treatment temperature;

$$\alpha_{2\text{oriz}} = \beta_{\text{oriz}} \cdot \sqrt[4]{t_i - t_a} + \frac{\varepsilon \cdot C_0}{t_i - t_a} \cdot \left[\left(\frac{t_i + 273}{100} \right)^4 - \left(\frac{t_a + 273}{100} \right)^4 \right] \text{ [kJ/m}^2 \cdot \text{h} \cdot \text{K], [8]} \quad (28)$$

$$\alpha_{2\text{vert}} = \beta_{\text{vert}} \cdot \sqrt[4]{t_i - t_a} + \frac{\varepsilon \cdot C_0}{t_i - t_a} \cdot \left[\left(\frac{t_i + 273}{100} \right)^4 - \left(\frac{t_a + 273}{100} \right)^4 \right] \text{ [kJ/m}^2 \cdot \text{h} \cdot \text{K], [8]} \quad (29)$$

$\alpha_{2\text{vert}}$ – coefficient of convection and radiation heat transmission through vertical walls during the maintaining period;

$\alpha_{2\text{oriz}}$ – coefficient of convection and radiation heat transmission through horizontal walls during the maintaining period;

$$Q_{\text{pierdere zidărie B}} = \Phi_B \cdot \tau_B, \text{ [kWh], [8]} \quad (30)$$

τ_B – sample maintaining time at the heat treatment temperature, [h].

After making the energy consumption calculations for the 15 situations (Appendix 2), when the values prescribed for the mechanical properties are obtained, the following variation of the energy consumption was obtained, according to Fig. 6.

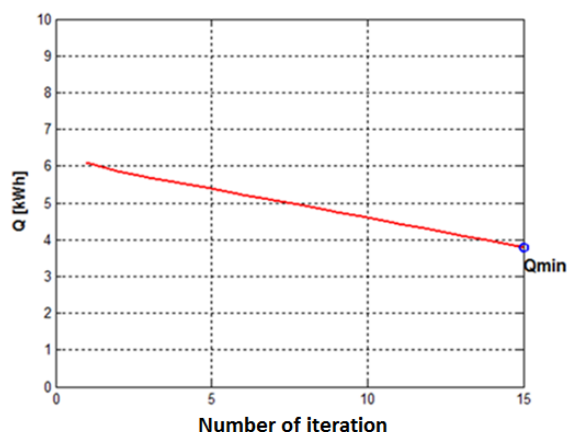


Fig. 5. Variation of energy consumption for the 15 iterations

4. Conclusions

From the data presented in Fig. 5, we can conclude that the optimum regimen that ensures the simultaneous accomplishment of the values of the mechanical properties imposed at the lowest energy consumption is the one given by iteration 15, having the following technological parameters:

- artificial ageing temperature $t = 123.52 \text{ }^\circ\text{C}$;
- ageing time $\tau = 6.021 \text{ hours}$;

The values of the mechanical properties obtained for these parameters are:

- mechanical resistance $R_m = 540.7 \text{ MPa}$;
- yield resistance $R_{p0.2} = 496.78 \text{ MPa}$;
- tensile elongation $A_5 = 8.49 \text{ \%}$;
- Brinell hardness $HB = 165.35$.

By applying the gradient method as a calculation variant for the thermal treatment optimization, the following aspects could be noticed:

- the artificial ageing temperature for complying with the properties restrictions imposed ranges between $120 \text{ }^\circ\text{C}$ and $123.5 \text{ }^\circ\text{C}$.

- the values of the thermal treatment time are between 6 and 20 hours.

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