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OPTIMIZATION OF THERMAL TREATMENT PARAMETERS FOR THE ALLOY AlZn4.5Mg1

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ABSTRACT

The paper presents the method of finding the optimal variant of thermal processing through artificial aging that is applied to a non-ferrous aluminum-based alloy.

The criterion based on which the optimum for the thermal process of artificial aging is obtained is that of the minimum consumption of energy consumed with the heat treatment furnace.

With the help of MATLAB, we created a graphic interface for the calculation simulation of the energy consumed by the treatment furnace depending on the process parameters and the identification of the optimal variant.

KEYWORDS: optimization, aluminum alloy, thermal treatment, mathematical modeling, prediction of property values, graphic interface

1. Introduction

Optimization is understood as the process of studying a problem that leads to the best and most suitable result compared to other possible results at the time, on which technical and/or economic decisions are made.

Considering the characteristics of the metallurgical industry, which are:

- high consumption of raw materials, fuels and energy;
- very complex technological processes;
- the large production capacities of the machines (furnaces, steel mills, rolling mills), the need to introduce management methods, both of technological processes and of metallurgical enterprises, which lead to considerable savings of raw materials, fuels and energy [1, 2] is evident.

"Like any technical system, metallurgical processes have certain technical and economic performances, performances that depend on the parameters, conditions and mode of exploitation of the system. That is, among the possibilities of choosing these parameters and existing conditions at a given moment, those that will ensure the best technical-economic performances of the process (choice of optimal parameters) must be selected" [2].

The optimization of any technological process is based on a mathematical model that must describe that process as faithfully as possible, the mathematical model being the main element in managing the process. Hence the immense importance of obtaining a mathematical model that very faithfully describes the respective process, which means that between the model and the described process there must be as high a concordance as possible [3].

The achievement of the optimal solution is done by highlighting some values of the independent variables, so that the best value for the objective function (the function to be optimized) results. The phrase optimal value of the objective function means, depending on the case, its maximum or minimum value.

The choice of the objective function is the most important step in solving an optimization problem. The efficiency of the process is given by several indicators, not just by one; that is why it is necessary to choose the most representative or complete indicator and finally check how the optimal solution corresponds with the other indicators.

The performance function (objective, optimization criterion) expresses the dependence between the main independent variables and the main desired performance in the management of the process [3].

The performance function is expressed by the relation [2]: $Y = Y(X_1, X_2,... X_n)$.

The performance function is the unique and objective criterion for process optimization and management [3]. Typically, the performance function represents an explicit economic criterion (for example: the manufacturing price of a product, maximum profit, etc.), but it can also be a non-economic criterion, but which is economically involved (as used in metallurgy extractive, where the obtained product undergoes subsequent changes) such as: productivity of aggregates (t/h; t/V of the aggregate, etc.), specific consumptions (raw materials/unit of product; electricity/unit of product, etc.), yields metallurgical (metal extraction, alloying element inclusion yields, impurity removal yields), etc. [4].

Optimization methods are generally reduction methods, which highlight the minimum of a "U" function of "n" real variables, which is called a goal function or objective function. Hence their name of methods for minimizing functions of several variables. Of course, the problem of finding the maximum returns to the minimization of the function with changed sign. Decreasing paths have global convergence, which means they allow finding the solution even if the starting point is far from the solution. Optimization methods belong to a very wide field of applicability. In other words, most natural or economic phenomena are compromises between contradictory causes and as such a lot of the problems of engineering, economics, statistics, mathematics, medicine, but more precisely decision-making processes can be mentioned as optimization problems. In other words, most numerical methods can be renamed as optimization problems [4].

2. Experimental conditions

Materials intended for experimentation are aluminum alloy from the Al, Zn, Mg, Cu system, with the chemical composition noted in Table 1.

The mechanical properties of the alloy according to EN 485-2-2007 are noted in Table 2.

Table 1. *Materials intended for experiments according to EN 485-2-2007*

AlZn4.5Mg1	**Zn**	**Mg**	**Cu**	**Si**	**Fe**	**Cr**	**Mn**	**Al**
%	4.5	1.4	0.2	0.35	0.4	0.35	0.5	rest

Table 2. *Mechanical properties of the alloy according to EN 485-2-2007*

Proprieties **Alloy**	**Rm [MPa]**	**$Rp_{0,2}$ [MPa]**	**A_5 [%]**	**HB**
AlZn4.5Mg1	350	250	10	104

The experimental research variant aimed to study the fluctuation of the mechanical properties of the alloys after the thermal treatment of artificial aging at different values of the time and temperature parameters [5].

Artificial aging was carried out at the following temperatures: 140 °C, 160 °C, 180 °C, 200 °C and 220 °C, and the following times for maintaining the alloy: 4 hours, 8 hours, 12 hours, 16 hours and 20 hours for each aging temperature.

The objective function in the variant of optimizing the thermal processing parameters of the studied alloy is represented by the energy consumption "Q = f(t, τ)" taking into account certain impositions considering the values of the investigated mechanical properties.

In order to find out which variant of thermal treatment from several variants resulting from the calculation with the help of the mathematical model created, represents the optimal variant economically and from the point of view of the property values, we proceed to calculate the thermal energy consumption Q, [kWh] for each among them.

The calculation of energy consumption in the form of heat (thermal energy) represents the calculation of the total energy consumed in the heat treatment furnace where artificial aging is carried out according to the relationship below:

$$Q_{total} = Q_{total\ oven} \tag{1}$$

Q_{total} - the amount of energy consumed for the thermal treatment; $Q_{total\ oven}$ - the amount of energy required to reach and maintain the treatment temperature during the entire period of performing the heat treatment.

The oven in which the heat treatment was carried out is an electric heating oven with silite bars, made of refractory fireclay brick, lined with mineral wool and with steel sheeting on the outside.

The energy consumed for the final thermal treatment will be determined after the thermal balance of the treatment furnace.

The energy consumption will be calculated by the amount of heat to be provided to reach and maintain the treatment temperature throughout the thermal treatment, according to relation (2) according to [6]:

$$Q_{\text{total oven}} = Q_A + Q_B, \qquad (2)$$

Q_A – the amount of heat (energy) consumed during the furnace heating period; Q_B - the amount of heat (energy) consumed during the maintenance of the temperature under heat treatment conditions.

The heat needed to increase the temperature inside the furnace from the ambient temperature to the treatment temperature is, [6]:

$$Q_A = Q_{\text{ac piece A}} + Q_{\text{ac masonry A}} + Q_{\text{perd masonry A}} \qquad (3)$$

$Q_{\text{ac piece A}}$ - the heat accumulated in the pieces (samples) during the heating period of the oven is given by relation (4) [7]:

$$Q_{\text{ac piece A}} = m_{\text{piece}} \cdot c_{\text{piece}} \cdot \Delta t1, \text{ [kJ]} \qquad (4)$$

m_{piece} - mass of samples, [kg]; Δt_1 = tt - ta, [°C]; Δt_1 - the temperature gradient between the treatment temperature tt and the ambient temperature ta; c_{piece} - the specific heat of the samples; $Q_{\text{ac masonry A}}$ - the heat accumulated in the furnace walls during the heating period is calculated with relation (5) [6, 7]:

$$Q_{\text{ac wall A}} = (m_{cs} \cdot c_{cs} + m_{vm} \cdot c_{vm} + m_t \cdot c_t) \cdot \Delta t_1, \text{ [kJ]} \qquad (5)$$

c_{cs} - specific heat of fireclay brick; c_{vm} - specific heat of mineral wool; c_t - specific heat of the plate; m_{cs} - the mass of the refractory fireclay brick of the furnace; m_{vm} - mineral wool mass used to insulate the oven; m_t - the mass of the steel sheet used to line the furnace; $Q_{\text{perd masonry A}}$ - the heat lost through the furnace walls during the heating period and is calculated using the thermal flow, ΦA [6, 7]:

$$Q_{\text{perd masonry A}} = \Phi_A \cdot \tau_A, \text{ [Wh]} \qquad (6)$$

τ_A - heating time of the oven interior, [h]; Φ_A - heat flow during the heating period, period A, is [7]:

$$\Phi_A = \Phi_{\text{horizA}} + \Phi_{\text{vert A}}, \text{ [W]} \qquad (7)$$

Φ_{orizA} - thermal flow through the horizontal walls of the furnace during the heating period; Φ_{vertA} - thermal flow through the vertical walls of the furnace during the heating period.

The heat required Q_B to maintain the samples, inside the furnace, at the treatment temperature is equal to the heat lost through the walls of the furnace during this entire period.

$$Q_B = Q_{\text{loss of masonry B}}, \text{ [kJ], [7]} \qquad (8)$$

This is also reproduced with the help of the thermal flow Φ_B [7]:

$$\Phi_B = \Phi_{\text{horizB}} + \Phi_{\text{vertB}}, \text{ [W]} \qquad (9)$$

Φ_{orizB} - thermal flow through the horizontal walls of the furnace during the period of maintaining the samples at the heat treatment temperature; Φ_{vertB} - thermal flow through the vertical walls of the furnace during the period of maintaining the samples at the heat treatment temperature.

$$Q_{\text{loss of masonry B}} = \Phi_B \cdot \tau_B, \text{ [kWh], [6]} \qquad (10)$$

τ_B - the time the samples are kept at the heat treatment temperature, [h].

By comparing each mechanical property, studied after applying the heat treatment, with a function of two variables $Y = f(t, \tau)$, it is possible to obtain a set of values for the studied mechanical properties if multiple interpolation is performed according to the variables t, τ, starting from to the values obtained through experimental research.

The MATLAB software package facilitates the interpolation of functions of two variables by using specific functions, such as *interp2* or *griddata2* [8, 9].

By interpolating the values for each studied mechanical property taking into account the two parameters of the final thermic treatment (t - artificial aging temperature, τ - artificial aging time), a volume of interpolated data of 289 values corresponding to each property was obtained.

Because aluminum alloys are "sensitive" to small changes in the treatment temperatures, a variation of the treatment temperature from five to five degrees was adopted, thus obtaining a number of 17 temperatures, between 140 °C and 220 °C.

The time for the artificial aging process was discretized from 4 hours to 20 hours with one-hour intervals, resulting in 17 interpolation values.

Under the given conditions, the goal of optimization is expressed by identifying among these data, only those that comply at the same time with the impositions of EN_485-2-2007 in terms of property values and are accompanied by the lowest energy consumption Q, [kWh].

3. Results and conclusions

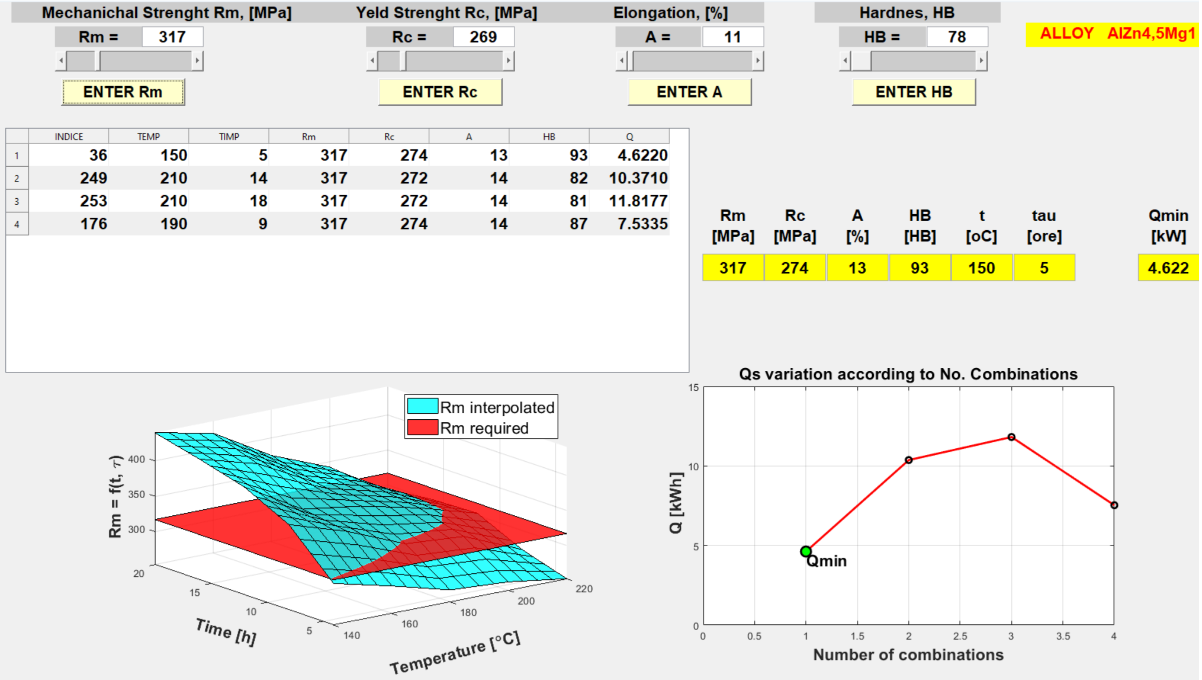
After performing the calculations, a number of 164 variants (combinations of technological heat treatment parameters) resulted for each property out of the 289 possible ones, which simultaneously meet the conditions imposed for the four mechanical properties:

- mechanical resistance, $Rm \geq 290$ MPa;
- yield strength, $Rp_{0.2} \geq 240$ MPa;

- elongation at break, $A_5 \geq 11\%$;
- Brinell hardness, HB ≥ 78 MPa.

For each of these 164 combinations, the energy consumption required for thermal processing was calculated.

The program developed in MATLAB shows that whatever value we impose, within the limits of 164, to any of the four studied properties, we will obtain a number of variants for which the optimum in terms of total energy consumption can be determined by calculation.

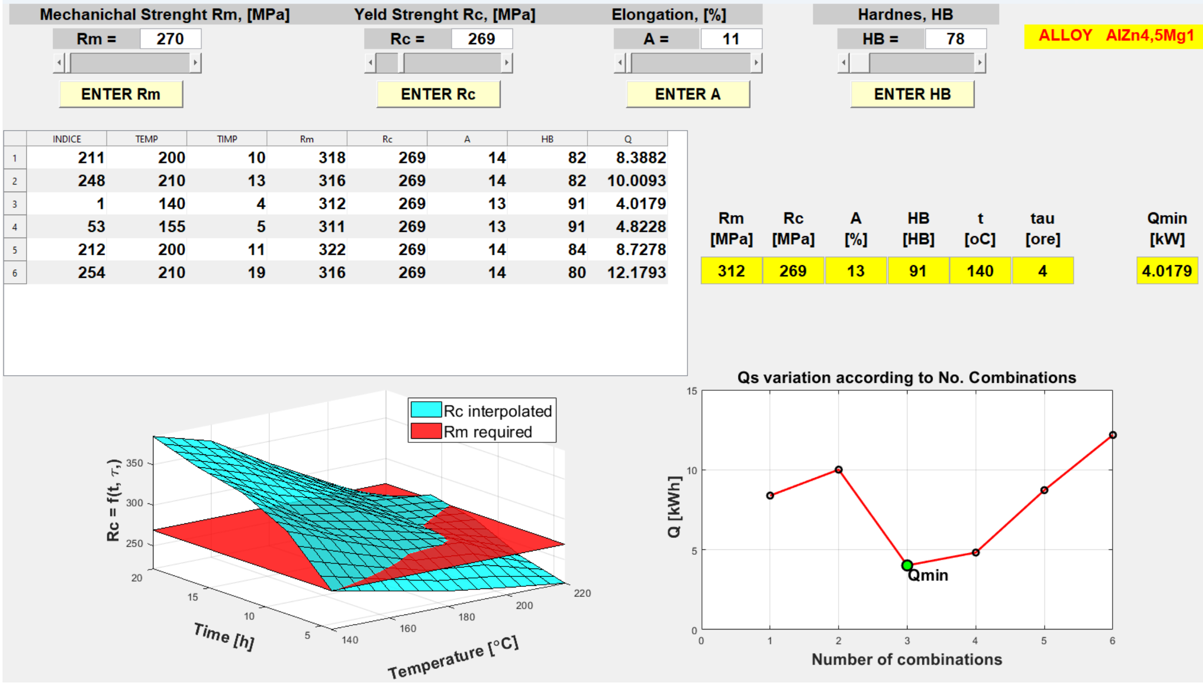


Rm = 317
Rc = 269
A = 11
HB = 78

	INDICE	TEMP	TIMP	Rm	Rc	A	HB	Q
1	36	150	5	317	274	13	93	4.6220
2	249	210	14	317	272	14	82	10.3710
3	253	210	18	317	272	14	81	11.8177
4	176	190	9	317	274	14	87	7.5335

Rm [MPa]	Rc [MPa]	A [%]	HB [HB]	t [oC]	tau [ore]	Qmin [kW]
317	274	13	93	150	5	4.622

Fig. 1. The values of the thermomechanical treatment parameters to obtain Rm = 317MPa



Rm = 270
Rc = 269
A = 11
HB = 78

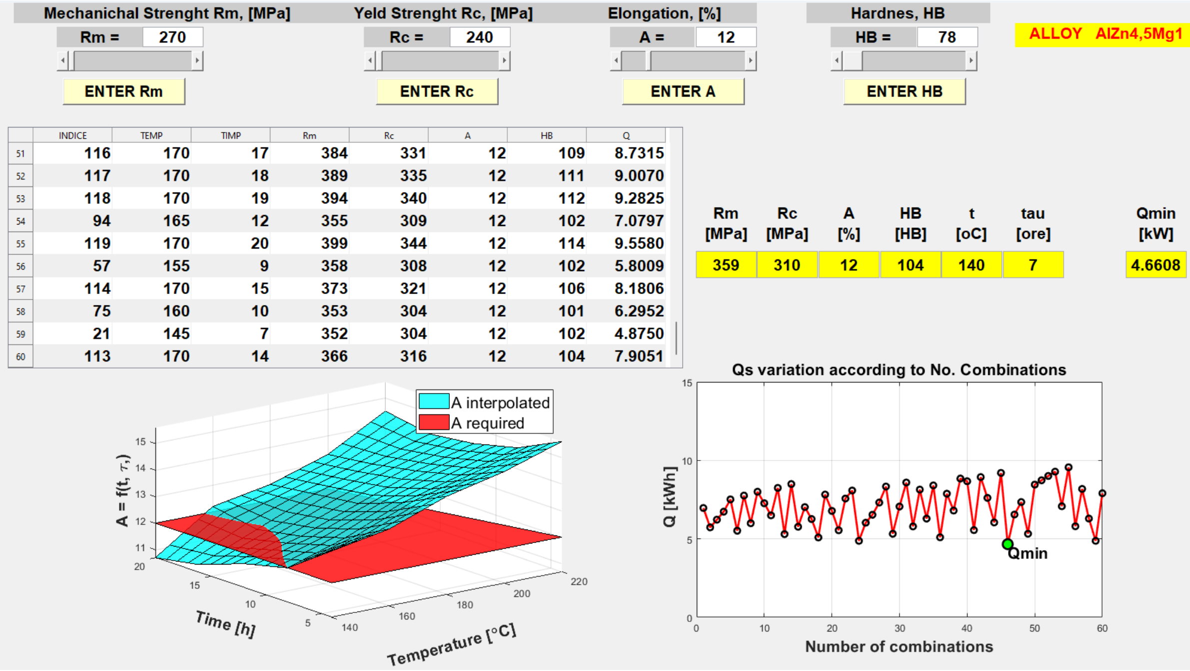
	INDICE	TEMP	TIMP	Rm	Rc	A	HB	Q
1	211	200	10	318	269	14	82	8.3882
2	248	210	13	316	269	14	82	10.0093
3	1	140	4	312	269	13	91	4.0179
4	53	155	5	311	269	13	91	4.8228
5	212	200	11	322	269	14	84	8.7278
6	254	210	19	316	269	14	80	12.1793

Rm [MPa]	Rc [MPa]	A [%]	HB [HB]	t [oC]	tau [ore]	Qmin [kW]
312	269	13	91	140	4	4.0179

Fig. 2. The values of the thermomechanical treatment parameters to obtain $Rp_{0.2}$ = 269 MPa

The graphical interface made with the help of this program allows viewing those possible situations and choosing a fairly large number of values for any of the four properties, as shown in Figures 1-4.

Figure 1 shows the situation when, for an imposed mechanical resistance of 317 MPa, the optimal option among the 5 possible, from the point of view of energy consumption, is the option in which the technological parameters of the heat treatment are: t = 150 °C, τ = 5 hours with an energy consumption of 4.622 kW.

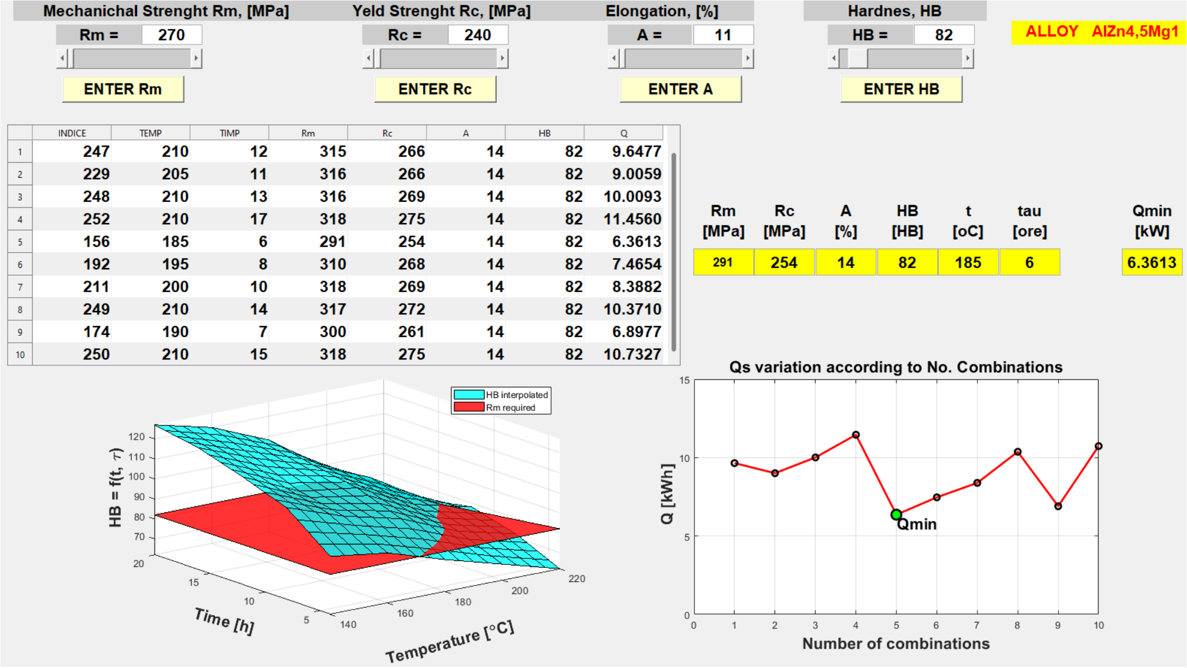


Mechanichal Strenght Rm, [MPa] Rm = 270
Yeld Strenght Rc, [MPa] Rc = 240
Elongation, [%] A = 12
Hardnes, HB HB = 78
ALLOY AlZn4,5Mg1

	INDICE	TEMP	TIMP	Rm	Rc	A	HB	Q
51	116	170	17	384	331	12	109	8.7315
52	117	170	18	389	335	12	111	9.0070
53	118	170	19	394	340	12	112	9.2825
54	94	165	12	355	309	12	102	7.0797
55	119	170	20	399	344	12	114	9.5580
56	57	155	9	358	308	12	102	5.8009
57	114	170	15	373	321	12	106	8.1806
58	75	160	10	353	304	12	101	6.2952
59	21	145	7	352	304	12	102	4.8750
60	113	170	14	366	316	12	104	7.9051

Rm [MPa]	Rc [MPa]	A [%]	HB [HB]	t [oC]	tau [ore]	Qmin [kW]
359	310	12	104	140	7	4.6608

Fig. 3. Values of heat treatment parameters to obtain A5 = 12 %



Mechanichal Strenght Rm, [MPa] Rm = 270
Yeld Strenght Rc, [MPa] Rc = 240
Elongation, [%] A = 11
Hardnes, HB HB = 82
ALLOY AlZn4,5Mg1

	INDICE	TEMP	TIMP	Rm	Rc	A	HB	Q
1	247	210	12	315	266	14	82	9.6477
2	229	205	11	316	266	14	82	9.0059
3	248	210	13	316	269	14	82	10.0093
4	252	210	17	318	275	14	82	11.4560
5	156	185	6	291	254	14	82	6.3613
6	192	195	8	310	268	14	82	7.4654
7	211	200	10	318	269	14	82	8.3882
8	249	210	14	317	272	14	82	10.3710
9	174	190	7	300	261	14	82	6.8977
10	250	210	15	318	275	14	82	10.7327

Rm [MPa]	Rc [MPa]	A [%]	HB [HB]	t [oC]	tau [ore]	Qmin [kW]
291	254	14	82	185	6	6.3613

Fig. 4. The values of the heat treatment parameters to obtain HB = 82 MPa

Figure 2 illustrates the situation in which, for a yield strength of 269 MPa, 6 possible cases appear, but among them the most economical is the one that has the following treatment parameters: t = 140 °C; τ = 4 hours; which give an energy consumption of Q_{tot} = 4.0179 kW.

Elongation at break of 12% is obtained from 60 possible variants, of which the optimal variant is the one with an energy consumption Q_{tot} = 4.66 kW for the optimal parameters shown in Figure 3, having the values: t = 140 °C, τ = 7 hours.

The HB hardness of 82 HB is obtained for t = 185 °C, τ = 6 hours, as shown in Figure 4, and the minimum value of Q_{tot} = 6.36 kW.

Also, with the help of this graphic interface, the values of thermal processing parameters can be highlighted, in tabular form, for those situations in which it is desired to obtain a certain value of one or more of the studied properties.

Simultaneously with the calculation of these values of the technological parameters of thermal treatment, the energy required to realize these variants is also calculated. Among these, the option with the lowest energy consumption is chosen and highlighted, i.e. the optimal option.

References

[1]. Ciucă I., Dumitriu S., *Modelarea şi Optimizarea Proceselor Metalurgice de Deformare Plastică şi Tratamente Termice*, Editura Didactică şi Pedagogică, Bucureşti, 1998.

[2]. Taloi D., *Optimizarea proceselor tehnologice – aplicaţii în metalurgie*, Editura Academiei, Bucureşti, 1987.

[3]. Şerban R., Dumitrescu T., *Metode de optimizare*, Editura Matrix Rom, Bucureşti, 1998.

[4]. Popescu D., Ionescu F., Dobrescu R., Ştefanoiu D., *Modelare în ingineria proceselor industriale*, Editura AGIR, Bucuresti, 2011.

[5]. Agus Sasmito, Mochammad Noer Ilman, Priyo Tri Iswanto, *Effects of rotational speed on the mechanical properties and performance of AA6061-T6 aluminium alloy in similar rotary friction welding*, Welding International, vol. 37, issue 9, 2023.

[6]. Ştefănescu D., Leca A., *et al.*, *Transfer de căldură şi masă. Teorie şi aplicaţii*, Editura didactică şi Pedagogică, Bucureşti, 1983.

[7]. Popa B., Man E., Popa M., *Termotehnică, agregate şi instalaţii termice*, Editura tehnică, Bucureşti, 1979.

[8]. Ghinea M., Fireţeanu V., *MATLAB - calcul numeric - grafică - aplicaţii*, Editura Teora, ISBN 973-601-275-1, Bucureşti, 1998.

[9]. Ghinea M., Fireţeanu V., *MATLAB. Calcul numeric. Grafică. Aplicaţii*, Ed. Teora, 2004.