Mathematical modelling and optimization of the thermomechanical treatment process applied to AlZn4.5Mg1Cu alloy

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Abstract: The paper presents the results of the experimental researches as a result of applying the thermomechanical treatment for the AlZn4.5Mg1Cu alloy used in the aeronautical industry, in order to optimize the processing parameters. The research is based on a laborious experimental thermomechanical processing program applied to AlZn4.5Mg1Cu aluminium alloy to obtain certain imposed values of the mechanical properties with the lowest possible expense. The objective function in the optimization of the investigated thermomechanical treatment regime is the energy consumption "Q = f (t, τ, ε)" taking into account some restrictions regarding the values of the investigated mechanical properties. The best value for the objective function is obtained by determining values for the independent variables of the thermomechanical treatment process, for which the conditions for obtaining values imposed on variables dependent on minimum energy consumption Q are met.

1. Introduction
The development of the aeronautical industry is very much related to the development of materials science and, in particular, of performance materials with special physical-mechanical properties. It is well known that the field of aircraft industry is a cutting edge field and therefore requires high performance materials. The AlZn4.5Mg1Cu alloy is part of the Al-Zn-Mg-Cu special alloy class. These alloys have the great advantage of having low density and high mechanical characteristics. This is why they are of particular interest to the aeronautical industry and the machinery industry [1-6].

Generally, these alloys have a deformability and a low mechanical strength which greatly changes with the application of thermal treatments [7, 8]. As a result of the aging process, natural or artificial, precipitations are formed in the structure of these alloys which lead to the hardening of the alloys. The mechanical properties of resistance become higher as the precipitations formed are finer, more dispersed and more numerous in the mass of the basic solution (solid solution) [1, 2, 4]. The complex interactions between base matrix dislocations and precipitated particles in the alloy structure as a result of aging lead to increased mechanical characteristics. Thermal processing takes place in solid state transformations which, if permitted in the alloy balance diagram, are an essential condition for carrying out a heat treatment, by quenching in solution and artificial or natural aging on an aluminium alloy [9, 10].

The increased resistance of Al-Zn-Mg-Cu alloys is directly proportional to the Zn or Zn + Mg content increase, thus generating Zn and Mg-rich fine metastable precipitated areas, which are the so-called GPs [1-4, 6]. The stages of the structural hardening mechanism following the application of thermal aging treatments are: formation of the supersaturated solid solution, by application of solution hardening, formation of Guinier - Preston zones during aging processes; first the precipitates form a metastable zone (η'), then as the temperature gradient is higher, these areas become stable, e.g. formation of precipitates MgZn2 [6, 10-13].
2. Experimental details

The chemical composition of the alloy from which samples for experimental research were made is shown in Table 1.

| Elements | Zn (%) | Mg (%) | Cu (%) | Si (%) | Fe (%) | Pb (%) | Mn (%) | Al (%) |
|----------|--------|--------|--------|--------|--------|--------|--------|--------|
| AlZn5,7MgCu | 4.5 | 1.4 | 0.2 | 0.35 | 0.4 | 0.35 | 0.5 | rest |

In order to use these materials in the aeronautical industry, especially in the machinery industry, after the thermomechanical processing, this alloy must acquire the mechanical properties prescribed in EN 485-2-2013 [14], which are shown in Table 2.

| Mechanical property | Alloy | Rm (MPa) | Rp0,2 (MPa) | A5 (%) | HB |
|---------------------|-------|----------|-------------|--------|-----|
| AlZn4,5Mg1Cu        | 350   | 250      | 10          | 104    |

This paper investigated the influence of thermomechanical treatment on the mechanical properties of the AlZn4,5Mg1Cu alloy.

Figure 1 presents schematically the thermomechanical processing to which the studied samples were subjected.

Thermomechanical processing consisted of the following:
- quenching in solution at 500 °C for 2 hours;
- preliminary artificial aging at 100 °C for 1 hour;
- cold plastic deformation with three degrees of deformation $\varepsilon_1 = 10\%$, $\varepsilon_2 = 20\%$ and $\varepsilon_3 = 30\%$ in order to ensure the dimensions set and to study the effect it has on the mechanical properties.
- final artificial aging at the following temperatures: $T_1 = 120^\circ C$, $T_2 = 140^\circ C$, $T_3 = 160^\circ C$ with a holding time: $\tau_1 = 8$ hours, $\tau_2 = 12$ hours, $\tau_3 = 16$ hours, for each temperature.

Cold lamination has been done to increase the hardness of the material, as well as to create favourable conditions for the occurrence of precipitations around dislocations in the subsequent final artificial aging.

At the end of thermomechanical processing, the sample sizes are: length $L = 200$ mm, width $l = 60$ mm, thickness $h = 5$ mm.
3. Experimental results and discussion

After performing the thermomechanical treatment, the samples were subjected to mechanical tests where the values of the properties $R_m$, $R_{p0,2}$, $A_5$, $H_B$ which are presented in Tables 3, 4, 5 are set. The values in the tables are the average of 5 measurements.

Table 3 Values of the mechanical properties after thermomechanical treatment with a degree of plastic deformation $\varepsilon = 10\%$

| Artificial aging time (h) | 120 °C | 140 °C | 160 °C |
|--------------------------|--------|--------|--------|
| $R_m$ (MPa)              | 302    | 318    | 294    |
| $R_{p0,2}$ (MPa)         | 216    | 229    | 227    |
| $H_B$ (%)                | 11,8   | 11,5   | 11,1   |
| $A_5$ (%)                | 98     | 112    | 117    |

Table 4 Values of the mechanical properties after thermomechanical treatment with a degree of plastic deformation $\varepsilon = 20\%$

| Artificial aging time (h) | 120 °C | 140 °C | 160 °C |
|--------------------------|--------|--------|--------|
| $R_m$ (MPa)              | 366    | 362    | 316    |
| $R_{p0,2}$ (MPa)         | 329    | 298    | 316    |
| $H_B$ (%)                | 9,6    | 9,7    | 9,2    |
| $A_5$ (%)                | 333    | 133    | 143    |

Table 5 Values of the mechanical properties after thermomechanical treatment with a degree of plastic deformation $\varepsilon = 30\%$

| Artificial aging time (h) | 120 °C | 140 °C | 160 °C |
|--------------------------|--------|--------|--------|
| $R_m$ (MPa)              | 385    | 282    | 8      |
| $R_{p0,2}$ (MPa)         | 330    | 131    | 329    |
| $H_B$ (%)                | 7.8    | 7.4    | 7.1    |
| $A_5$ (%)                | 354    | 362    | 384    |

The determination of the mechanical properties values revealed that values of the mechanical properties studied which correspond to the requirements of the specific norms in force [14] were not obtained for all combinations of the considered thermomechanical processing parameters (time, temperature, degree of plastic deformation).

The values of the studied mechanical properties are based on the values of the three parameters of the thermo-mechanical treatment regime and for this reason the mechanical properties were considered as functions of three variables: $R_m = R_m (T, \tau, \varepsilon)$, $R_{p0,2} = R_{p0,2} (T, \tau, \varepsilon)$, $A_5 = A_5 (T, \tau, \varepsilon)$, $H_B = H_B (T, \tau, \varepsilon)$. 
By using an interp3 specific function from the MATLAB program package, it was obtained the interpolation of the functions of three variables \( R_m = R_m (T, \tau, \varepsilon) \), \( R_p0, 2 = R_p0, 2 (T, \tau, \varepsilon) \), \( A_5 = A_5 (T, \tau, \varepsilon) \), \( H_B = H_B (T, \tau, \varepsilon) \).

Interpolation was performed in turn for all four mechanical characteristics studied according to the three parameters: \( T \) - the final artificial aging temperature, \( \tau \) - the final artificial aging time and \( \varepsilon \) - the degree of cold plastic deformation preceding the final artificial aging [15].

Aluminium alloys are "sensitive" to small variations in heat treatment temperatures and for this reason we set a five to five degree variation for the final artificial aging temperature. Thus, nine interpolated values for the treatment temperature were obtained in the range of: 120 °C and 160 °C.

The artificial aging time from 8 hours to 16 hours was discretized with an hour’s step, resulting in 9 interpolation values.

For the degree of plastic deformation in the range of 10% - 30%, a number of 21 incremental values having a 1% step were interpolated.

Interpolation resulted in a volume of 1701 interpolated values for each property.

The optimization of the thermo-mechanical process meant in these conditions, in the first stage, finding out of these 1701 data corresponding to each property, only those data that simultaneously fulfil the conditions imposed by EN 485-2-2013, and in the second stage the calculation of the energy consumption required for thermomechanical processing for all the situations identified in the first stage and choosing the variant for which \( Q \) energy is minimal [15, 16].

Calculation of energy consumption in the form of heat (thermal energy) was made by calculating the total \( Q_{total} \) energy consumed by the heat treatment furnace and the rolling mill used for plastic deformation. These calculations were made using the relationship below:

\[
Q_{total} = Q_{total\ furnace} + Q_{lam} \quad [17],
\]

where:

\( Q_{total\ furnace} \) - the amount of heat required to reach and maintain the treatment temperature throughout the heat treatment;

\( Q_{lam} \) - the amount of energy consumed for sample rolling.

\[
Q_{total\ furnace} = Q_A + Q_B, \quad [17],
\]

\( Q_A \) - the amount of heat (energy) consumed during the furnace heating period;

\( Q_B \) - the amount of heat (energy) consumed during the maintenance period at the heat treatment temperature.

\[
Q_{lam} = U \cdot I \cdot t_{lam} \cdot kWh \quad [17],
\]

\( Q_{lam} \) - energy consumed for cold plastic deformation;

\( U \) - the power supply voltage of the rolling mill motor;

\( U = 380 \) V;

\( I \) - the intensity of the electric current used for rolling, A.

The program developed in MATLAB with the help of the interp3 function and the mathematical equations of thermal balance (1), (2), (3) shows that for any value imposed from the total of 1701 to any of the four properties, a number of variants possible was obtained for which the optimum in terms of total energy consumption can be determined.

With the help of the program developed in MATLAB, a graphical interface was created, a graphical interface allowing visualization (simulation) of those possible situations and choosing a large number of values for any of the four properties.

Figure 2 shows an example of such a simulation.
Figure 2 Graphical interface for simulating possible situations from the point of view of the imposed mechanical characteristics and energy calculation Q

4. Summary and conclusions

The conclusions drawn from the research described in this paper were as follows:
- The existence of a dependence between the values of the mechanical strength properties and the degree of cold plastic deformation before the final artificial aging;
- The resistance properties values are inversely proportional to the thermal treatment temperature and directly proportional to the values of the artificial aging time;
- The mechanical strength of the alloy processed records the highest values for the artificial aging time of 16 hours and the temperature of 120°C and the lowest resistance values are recorded for the 8 hour aging and the temperature of 160°C;
- With increasing the final artificial aging time and lowering the aging temperature as well as increasing the degree of plastic deformation, the alloy’s elongation value is decreasing;
- The MATLAB graphical interface allows simulation and identification based on mathematical computation of Qtotal's minimum value, which is the optimum for thermomechanical processing;
- With this graphical interface, the values of the thermomechanical processing parameters can be highlighted in tabular form for those situations in which a certain value of one or more of the studied properties is to be obtained.

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