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INFLUENCE OF THERMOMECHANICAL TREATMENT ON PROPERTIES OF Al-Mg-Si ALLOY

ZLATANKA MARTINOVA, DIMITAR DAMGALIEV

University of Chemical Technology and Metallurgy, Sofia, Bulgaria

ABSTRACT

The effects of pre-aging conditions (90°C to 140 °C/ 15 min to 4 h) followed by 95% deformation and the final aging time and temperature (130°C to 170°C/1h to 8 h) on strength, elongation and electrical conductivity of a thermomechanically treated 6201 alloy were examined. Regression models were derived for each of the properties. Treatment conditions for maximum strength or conductivity were determined using models and multicriterial optimization procedure. A compromised treatment regime for optimal balance between strength/ conductivity/ ductility of the wires was established.

Keywords: pre-aging, deformation, mathematical models, strength and electrical conductivity

1. INTRODUCTION

Limited information is available for the Al-Mg-Si alloys, subject to TMT with stepped aging. Conclusions about its effectiveness are based on changes of either hardness or strength, obtained after selected pretreatment conditions or single regimes of TMT. Nevertheless, from the previous works [1-4] it is clear that the main parameters are time and temperature of pre-age, amount of cold work, time and temperature of the final aging. Hence, to establish the beneficial or detrimental effects and optimal regimes of TMT is necessary to have a quantitative relation between the processing parameters and required properties. Besides, for many applications it is important to derive suitable treatment conditions that provide a proper combination between different properties. For the 6201 wires $\phi \leq 3.37$ mm an ultimate tensile strength ≥ 317 MPa, combined with an electrical conductivity ≥ 52.5% IACS (30.45 $m.\Omega^{-1}.mm^{-2}$) and enough ductility is required.

In the present work, which is a part of extensive study, we aim to develop regression models that connect the above mentioned response variables with time and temperature of pre-age and temperature and time of final aging of 6201 alloy subjected to TMT. The models will allow determining of the processing conditions that provide optimal values of wire properties.

2. EXPERIMENTAL PROCEDURE

The alloy used in the present investigation was received as a continuously (Properzi) produced rod 9.52 mm diameter, long term stored in coil at ambient temperature i.e. in natural aged condition. The rod chemical analysis in mass % was: Mg 0.62%, Si 0.57%, Fe 0.23%, Cu 0.052%, V 0.0032%, Mn 0.0027%, Ti° 0.0129%. The rods were solutionized (ST) at 520°C for 4 hours and then quenched (Q) in cold water. Immediately after quenching rod samples were pre-aged (PI) at a different pre-aging time and temperatures. The pre-aged rods were then drawn (D) to 2.11 mm wire on a one pass drawing block, thus simulating the non-slip drawing process. Samples, cut from the wire were aged at different combinations of temperature and time of final aging (PII). The applied thermomechanical processing (TMT) further will be abbreviated as ST-Q-PI–D-PII. The deformation in all experiments was kept ~95%, while the intervals of variation of each factor were:

$15 \leq X_1 \leq 240$ – Pre-aging time τ_{PI} [min]

$90 \leq X_2 \leq 140$ – Pre-aging temperature T_{PI} [°C]

$0 \leq X_3 \leq 8$ - Final aging time τ_{PII} [hours]

$120 \leq X_1 \leq 170$ – Final Aging temperature T_{PII} [°C]

The electrical conductivity γ [m Ω^{-1}.mm^{-2}], ultimate tensile strength R_m [Nmm^{-2}] and elongation A [%] were investigated as response variables Y_1, Y_2 and Y_3, respectively.

3. RESULTS

The collected data from more than 300 experiments were processed using MINITAB statistical software. Regression models describing each of the properties were derived. A third order polynomial model was obtained for electrical conductivity, while fourth order polynomial models describe the tensile strength and elongation.

The calculated values of the determination coefficients R^2 are correspondingly 0.99, 0.894 and 0.76 i.e. the models are accurate enough. They were used to determine the processing conditions that provide best values of Y_1, Y_2 and Y_3. An optimization procedure was applied to maximize each property separately. It was found that the TMT conditions which give maximum of electrical conductivity $Y_1 = 32.29$ [m.Ω^{-1}.mm^{-2}], are $X_1 = \tau_{PI} = 90$ min at $X_2 = T_{PI} = 90$°C, final aging for $X_3 = \tau_{PII} = 8$ hours at $X_4 = T_{PII} = 170$°C.

Maximization of the ultimate tensile strength (R_m) Y_2 = 392 Nmm^{-2} is obtained when pre-aging conditions are $X_1 = \tau_{PI}$ = 15min at $X_2 = T_{PI}$ = 110°C, combined after deformation with final aging for $X_3 = \tau_{PII}$ = 2 hours at $X_4 = T_{PII}$ = 155°C.

The maximum value for elongation (A) Y_3 = 9.4 % was obtained at the following TMT conditions: pre-aging time $X_1 = \tau_{PI}$ = 120 min at pre-aging temperature $X_2 = T_{PI}$ = 120°C; final aging for $X_3 = \tau_{PII}$ = 8 hours at $X_4 = T_{PII}$ = 130°C.

As it was expected different processing conditions were required for each of the investigated properties to reach its maximum. In order to find a proper result, beneficial to all properties, compromise multi criteria optimization utilizing generalized function of desirability was done. The optimal values of properties and factors were determined as follows:

Y_1 (γ) = 30,95 $m.ohm^{-1}.mm^{-2}$	X_1= 120 min
Y_2 (R_m) = 345 Nmm^{-2}	X_2= 120°C
Y_3 (A) = 6,1 %	X_3= 8 hours
	X_4= 165°C.

Based on the obtained compromised determination it was possible to explore the influence of the given pair of factors on the investigated properties by keeping the other two factors fixed at their optimal values.

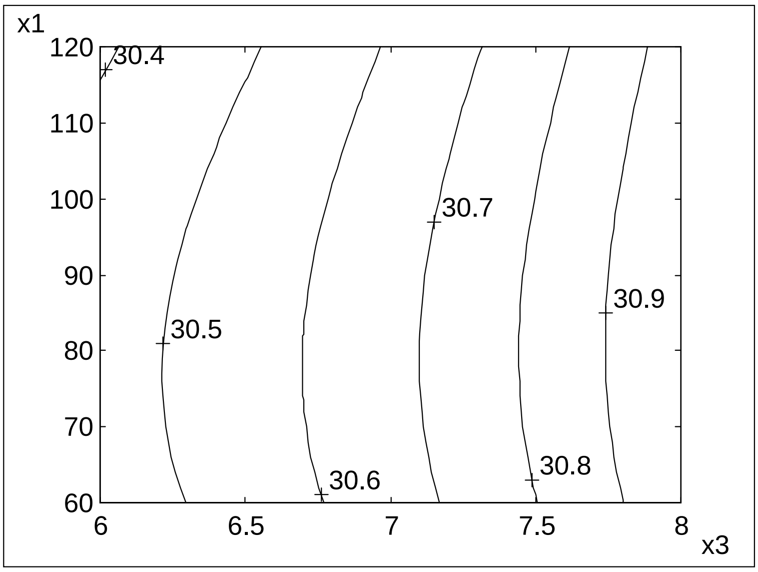

Fig. 1. Changes of electrical conductivity] [m. $\Omega^{-1}.mm^{-2}$] with pre-aging (X_1)[min] and final aging (X_3) times [hrs]; TMT: ST-Q-$PI_{120°C}$-$D_{95\%}$-$PII_{165°C}$

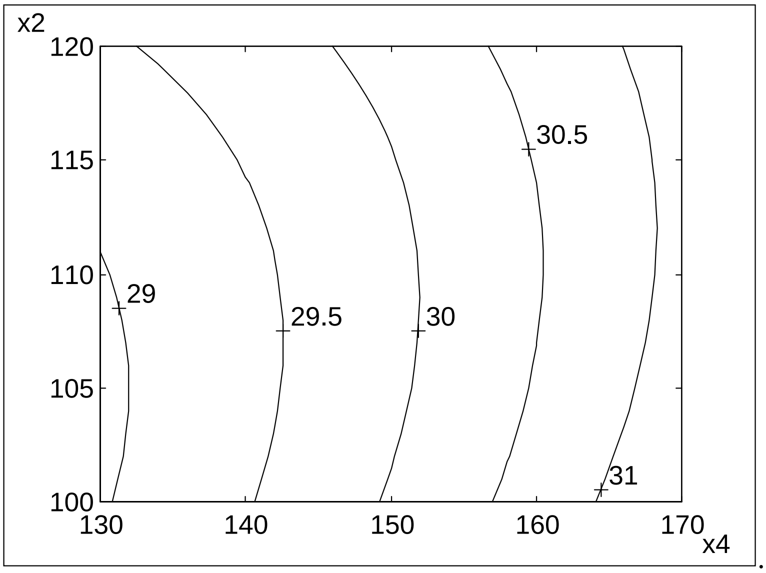

Fig. 2. Changes of electrical conductivity [m. Ω^{-1}.mm^{-2}] with pre-aging (X_2) and final aging (X_4) temperatures [°C]; TMT: ST-Q-PI$_{120min}$-D$_{95\%}$-PII$_{8\ hours}$

Fig. 1 to 6 depicts part of 18 constructed graphs used for interpretation of mutual dependencies of factors and response variables. The analysis revealed that the pre-aged and deformed samples (ST-Q-PI-D) exhibit higher conductivity when they are either isothermally or isochronally aged at higher temperature of PII. Pre-aging time was found to exert weak influence on electrical conductivity as compared with the time and temperature of final aging and temperature of pre-aging. Increasing of PII- time positively affects the electrical conductivity (Fig. 1). The simultaneous increase of pre-aging temperature and final aging temperature (Fig. 2) results in higher conductivity after given time of PI and PII but again more significant factor is the TP$_{II}$.

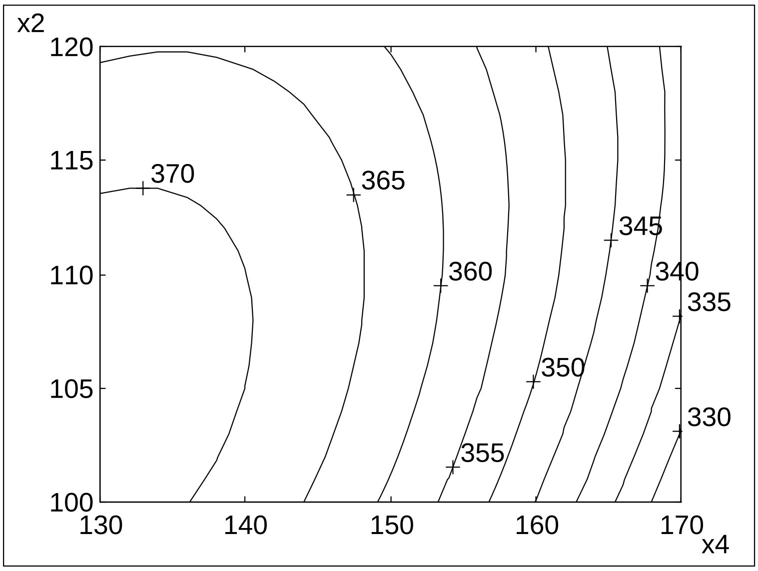

Fig. 3. Changes of tensile strength (MPa) with pre-aging (X_2) and final aging temperatures (X_4) [°C] TMT: ST-Q- PI_{120min}-$D_{95\%}$-PII_{8hours}

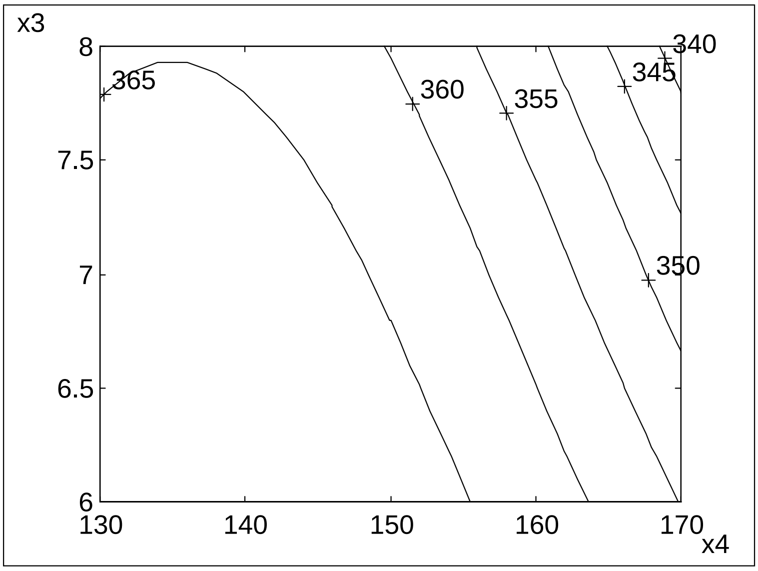

Fig. 4. Changes of tensile strength (MPa) with final aging (X_4) temperature [°C] and time (X_3)[hrs] TMT: ST-Q- $PI_{120°C\ 120min}$-$D_{95\%}$-PII

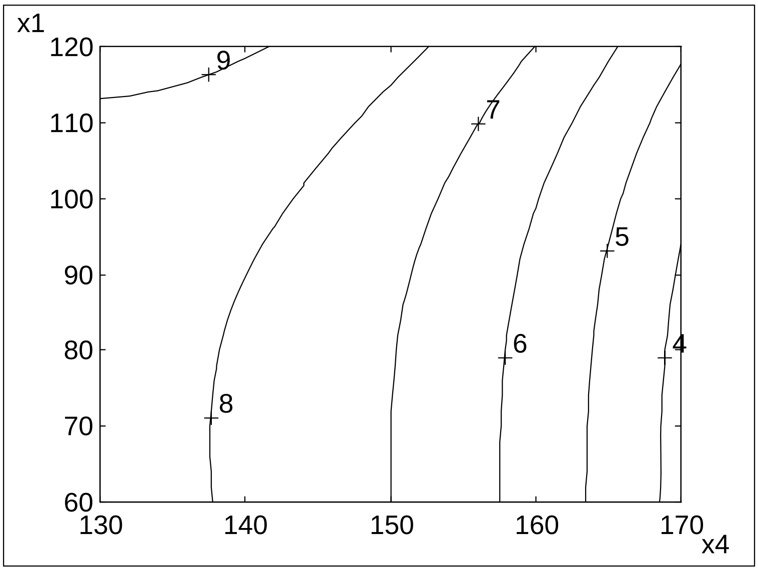

Fig. 5.Changes of tensile elongation (%) with pre-aging time (X_1) [min] and temperature of final aging (X_4) [°C]; TMT: ST-Q-$PI_{120°C}$-$D_{95\%}$-PII_{8hours}

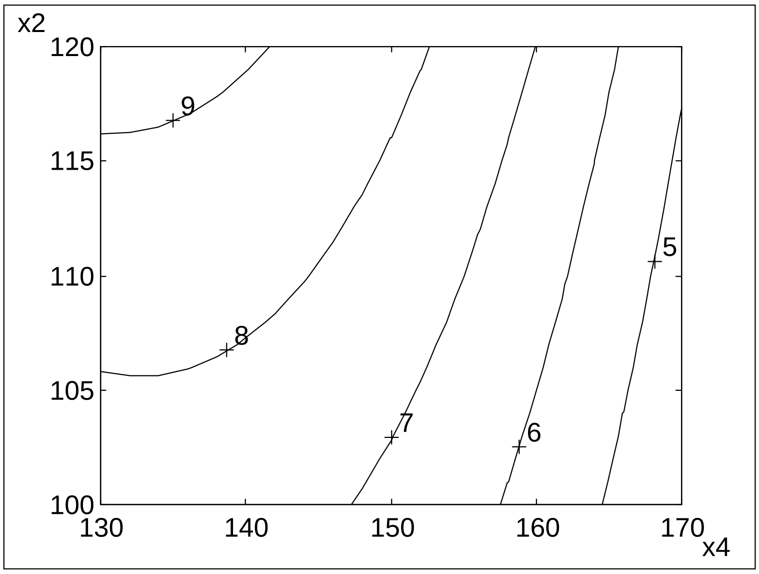

Fig. 6. Changes of tensile elongation (%) with pre-aging (X_2) and final aging (X_4) temperatures [°C]; TMT: ST-Q-PI_{120min}-$D_{95\%}$-PII_{8hours}

8 hours final aging carried out at increasing temperature from 130 to 170°C markedly reduces both ultimate strength and elongation of wires pre-aged at given conditions (Figures 3 and 6). Tensile properties are affected in a more complicated manner by simultaneous change of pre-aging and final aging

temperatures. The dependence of Rm on T_{PI} and T_{PII} shows that tensile strength reaches maximum at T_{PII} around 130 -135°C, performed on pre-aged at around 106-108°C wires. Simultaneous increase of both factors leads to the lowering of strength. But as it is seen on the diagrams when temperature T_{PI} is chosen from 105 up to 120°C and T_{PII} is quite close to it – 130 - 140°C good combination between strength/elongation is obtained. Figure 4 shows isolines of Rm for ST-Q- $P_{I\ (120°C/\ 120min)}$- $D_{95\%}$ samples at simultaneous change of final aging time and temperature. Much of the work hardening is still preserved after 6 –7 hours aging at 130 -140°C. Increase of conductivity on aging at 160 -170°C is accompanied with softening. By increasing the pre-aging time and temperature at constant optimal values of PII a distinct increase of tensile elongation and some strengthening is observed. Longer pre-aging time at 120°C beneficially influence the elongation after final aging and provides better combination between strength and elongation. Increase of final aging temperature lowers elongation but values ~9% are still preserved when pre-aging is performed at 115-120°C for 1.5-2 hours and temperature of final aging do not exceed 140°C (Figures 5 and 6).

It should be emphasized again that all above-discussed effects were established in the compromised area of factors and the three investigated response variables.

4. DISSCUSION

It is well known that any pre-aging after ST-Q at ambient or moderate temperatures modifies the structure of the quenched Al- Mg -Si alloys because it leads to clustering reactions and GP-I zones formation. The size and distribution of zones determined their mechanical and thermal stability during deformation and higher temperature ageing respectively [5, 6] and depend on the pre-treatment parameters. In our experiments the same severe plastic deformation was applied to a partially decomposed during different pre-ageing treatments α_{Al}- supersaturated solid solution. The main process governing properties on this stage is the work hardening and interaction between preexisting zones structure and dislocations, leading either to a partial/ full reversion or stabilization of clusters (zones) and to changes in the character of dislocation distribution. The preexisting dislocation structure can influence greatly the aging process through increased diffusion rate, number of potential sites of heterogeneous precipitation and alloy susceptibility to recovery and recrystallization. The strength of Al-Mg-Si alloys after T6 or T8 treatments is related to size, shape, volume fraction and distribution of precipitated strengthening phases $\beta''$and $\beta'$and their interaction with dislocations. The electrical conductivity is a function of the purity of the matrix and for increased ductility uniformly distributed strain should be achieved. That’s why different pre- and final ageing treatment was found to maximize the investigated properties. The compromised final aging regime (165°C), found in this work is close to those in conventional T8 for this alloy. The obtained values of properties are comparable with the results, reported in [3], and do not differ significantly from those, obtained in TMT experiments without presaging.

5. CONCLUSIONS

From the obtained mathematical models and applying optimization procedure it can be concluded, that

1. The optimal combination of properties in TMT with 95% deformation tends to be approached when temperature of pre-aging is around 120°C for 2 hours, and final aging is around 165 °C for 8 hours. Mechanical and electrical properties obtained will be as follows: Rm -345 MPa, elongation - 6%, electrical resistivity 3,231μΩ.cm, conductivity 30.95 m. Ω^{-1}.mm^{-2} (53.36 % IACS) wire 2,11 mm.

2. Application of TMT having pre-aging in temperature range of GP I-zones formation and high degree of deformation followed by final aging up to 150°C favors strength/ ductility combination.

3. In the chosen interval of variations of factors the effect of final aging conditions on properties is stronger compared to pre-aging temperature and time.

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