EFFECT OF THE T6 HEAT TREATMENT ON CHANGE OF MECHANICAL PROPERTIES OF THE AlSi12CuNiMg ALLOY MODIFIED WITH STRONTIUM

The paper presents test results concerning an effect of the heat treatment on microstructure and mechanical properties of eutectic EN AC-AlSi12CuNiMg (EN AC-48000) alloy according to the EN 1706:2010 (tensile strength – $R_m$, hardness – $HB$) modified with strontium. Solution heat treatment and ageing treatment temperature ranges were selected on base of heating (melting) curves recorded with use of the ATD method. Temperatures of the solution heat treatment were 500, 520, and 535°C ±5°C, while the solution time ranged from 0.5 to 3 h (0.5; 1.5 and 3 h). Temperature of the solution heat treatment amounted to 180, 235 and 310°C, while the ageing time ranged from 2 to 8 h (2, 5 and 8 h).

Obtained results have enabled determination of optimal parameters of the T6 heat treatment in aspect of improvement of tensile strength $R_m$ and hardness $HB$ of the alloy, with reduced time of individual treatments and determination of mathematical relationships enabling prediction of these mechanical properties.

Keywords: aluminum alloys, heat treatment, mechanical properties

1. Introduction

Contemporary engineering materials are required to be light weight and corrosion resistant, coupled with high strength and hardness. In the recent years, aluminum alloys had attracted attention of many researchers, engineers and designers, as promising structural materials for automotive industry or aerospace applications [1-4]. To the most popular casting alloys belong silumins (Al-Si), which are characterized by low density equal to about 3.0 g/cm$^3$; low density advantageously increased weight to strength, which is determined by ratio between tensile strength and specific gravity ($R_m/\rho$) [5].

Mechanical properties of the Al-Si casting alloys, especially elongation, depend on alloy’s structure and eutectic silicon, which may have an acicular or lamellar form [6]. Strontium is also used as modifier for the Al-Si-Mg alloys [7]. It possesses certain advantages over the sodium in that it is easier to add to the melt, and it offers a semi-permanent modified Al-Si-Mg alloys.

The addition of alloying elements such as Mg and Cu make the alloys heat treatable, further improving their mechanical properties and allowing their use in new, more demanding applications (e.g. engines, cylinder heads, etc.) [1]. The most used heat treatment for these Al-Si-Cu cast alloys is the solution heat treatment followed by age hardening, that is required for the precipitation of the Al$_2$Cu hardening constituent. The solution heat treatment of the Al-Si-Cu cast alloys affects the microstructure, improvement of eutectic silicon morphology (fragmentation, spheroidization and coarsening) and ensures changes in fracture zones [8-10].

The T6 heat treatment comprises three stages: solution heat-treating, quenching and artificial aging [11-12]. Application of suitable parameters of individual heat treatments determines obtainment of improved mechanical properties of processed materials [13-17].

The AlSi12CuNiMg eutectic aluminum alloy, investigated in the present work, is widely used for load-bearing structural components, for example: pistons for combustion engines,
gears or pump parts, and wear-resistant and heat-resistant parts due to high strength at increased temperature and low thermal expansion.

Objective of the present work is to determine optimal parameters of the T6 heat treatment for the EN AC-AlSi12CuNiMg alloy in aspect of improvement of its mechanical properties ($R_m$ and $HB$) and a possibility of their prediction.

2. Experimental procedure

Investigated alloy was melted in crucible-type electric furnace and underwent treatments of refinement (Rafal 1 – 0.4% mass of charge) and modification (AlSr10 – 0.4% mass of charge).

Chemical composition of the investigated alloy is presented in the Table 1. Analysis of chemical composition was performed with use of spectrometric method (spectrometer GDS 850A type).

![Fig. 1. Melting and crystallization curves from the ATD of the investigated alloy](image)

TABLE 1

| Alloy          | Si  | Cu  | Zn  | Fe  | Mg  | Ti  | Mn  | Ni  |
|---------------|-----|-----|-----|-----|-----|-----|-----|-----|
| EN AC-AlSi12CuNiMg | 11.53 | 1.15 | 0.02 | 0.29 | 1.30 | 0.03 | 0.20 | 1.06 |

The heat treatment was performed for the modified alloy. It consisted in operations of solution heat treatment and ageing treatment. Temperatures of these treatments were selected on base of values of points on melting (heating) curves recorded with the ATD method (Fig. 1), using automated "Crystaldimat" analyzer.

In the Table 2 are presented parameters of the heat treatments for three-stage plan of the testing with four variables.

Test pieces were prepared in accordance with the PN-88/H-88002 standard. Static strength tests were performed on the ZD-20 tester. Measurement of the Brinell hardness was performed according to the PN-75/H04350 standard with use of the Brinell hardness tester of the PRL 82 type, with $\varnothing$ 10 mm steel ball, at 9800 N load sustained for 30 seconds. Microstructure photos of the alloy were made with use of the Neophot 32 optical microscope and the MultiScan picture analyzer. To obtain the dependencies and plot the diagrams depicting effect of the heat treatment parameters on the mechanical properties of the investigated alloys it has been used the "Statistica" ver. 10 software, from the StatSoft Company.

3. Results and discussion

Refined and modified alloy has been subjected to heat treatment T6 type. The tensile strength $R_m$ was determined for the refined and modified alloy (initial alloy), and the alloy after solution heat treatment and ageing treatment.

In the Fig. 2 are presented average values of the tensile strength $R_m$ of the EN AB-48000 alloy after the heat treatment, in reference to the alloy without the heat treatment for 27 systems of applied testing plan.

TABLE 2

| Designation | Ageing temperature, [$^\circ$C] | Ageing time, [h] | Designation | Solutioning temperature, [$^\circ$C] | Solutioning time, [h] |
|-------------|-------------------------------|-----------------|-------------|-------------------------------------|---------------------|
| A           | 180                           | 2               | D           | 500                                 | 0.5                 |
| B           | 235                           | 5               | E           | 520                                 | 1.5                 |
| C           | 310                           | 8               | F           | 535                                 | 3.0                 |
The tensile strength $R_m$ obtained for the refined and modified alloy amounted from 218 to 230 MPa. After performed heat treatment, the tensile strength $R_m$ was contained within range from 184 to 393 MPa.

In the Fig. 3 are depicted spatial diagrams of an effect of temperature and duration of solutioning and ageing treatments on change of the tensile strength $R_m$ of the investigated alloy.

Making comparison of obtained average values of the parameters from tests of the alloy after heat treatment and without heat treatment, one ascertained a growth of the tensile strength $R_m$ up to 170% (system no.13, Fig. 2) with respect to the modified alloy, without the heat treatment.

The highest tensile strength $R_m = 393$ MPa was obtained for: solutioning temperature $520^\circ$C, solutioning time 1.5 hour, ageing temperature $180^\circ$C and ageing time 5 hours. Whereas, the lowest tensile strength $R_m$ (176 MPa) was obtained in case of the test pieces solutioned for 1.5 hour at temperature $500^\circ$C, and aged for 2 hours at temperature $310^\circ$C.

Based on results of the performed investigations one described, with mathematical dependence (1) in form of second-degree polynomial, an effect of heat treatment parameters on change of the tensile strength $R_m$ of the alloy.

\[
R_m = -18198.7 - 0.1x_1^2 + 46.3x_2^2 - 5.1x_3^2 + 1.4x_3 - 0.4x_4 - 0.6x_1x_2 + 0.9x_2x_4 - 0.1x_3x_4 \quad [\text{MPa}]
\]

(1)

where: $x_1$ – solutioning temperature, $x_2$ – solutioning time, $x_3$ – ageing temperature, $x_4$ – ageing time. Correlation coefficient (for $\alpha = 0.05$): $R = 0.99$; $R^2 = 0.97$; corr. $R^2 = 0.93$.

Obtained values of the correlation coefficient close to 1 have confirmed that mathematical dependence (1) sufficiently describes effect of heat treatment parameters on change of the tensile strength $R_m$ of the investigated alloy. In the Fig. 4 are presented experimental (real) and predicted values of the tensile strength $R_m$ of the investigated alloy.

The hardness $H_B$ of the alloy after refinement amounted to $75 \ H_B \ 10/1000/30$. The modification did not result in any visible growth of the hardness, which amounted to $77 \ H_B \ 10/1000/30$. After performed heat treatment of the alloy, obtained hardness $H_B \ 10/1000/30$ was included within range from 59 to 143.

In the Fig. 5 are presented average values of the hardness $H_B$ for the EN AC-AlSi12CuNiMg (EN AB-48000) alloy after the heat treatment with respect to the values obtained for the
alloy without the heat treatment for 27 systems of applied plan of the testing.

Fig. 5. Change of the hardness HB of the investigated alloy for individual systems of the testing plan

Spatial diagrams of the effects of temperature and time of solutioning and ageing treatments on change of the hardness HB of the investigated alloy are shown in the Fig. 6.

Fig. 6. Effect of temperature and time of the solutioning on hardness HB of the EN AB-48000 alloy: a) for $A = 180^\circ$C, 2 hours, b) for $F = 535^\circ$C, 1.5 hours

Making comparison of obtained average parameters from the investigations of the alloy after the heat treatment and without the heat treatment, one confirmed the highest growth of the hardness HB in case of the system no. 13 (solutioning temperature – 520°C; solutioning time – 1.5 hour; ageing temperature – 180°C; ageing time – 5 hours), and the system no. 25 (solutioning temperature – 535°C; solutioning time – 0.5 hour; ageing temperature – 180°C; ageing time – 5 hours) (143 HB 10/1000/30). The lowest hardness HB was obtained in case of the systems 7, 9, 18, 26, which were characterized by high temperature of the ageing (310°C) in complete range of ageing times. Its value was included within range of 59-65 HB 10/1000/30, what represents a decrease with respect to refined and modified alloy.

Based on results of the performed investigations one described, with mathematical dependence (2) in form of second-degree polynomial, an effect of heat treatment parameters on change of the hardness HB of the alloy.

$$HB = -1252.03 + 4.58x_1 + 101.1x_2 - 1.23x_3^2 + 0.94x_3$$
$$-2.14x_4 - 0.4x_2^2 - 0.18x_1x_2 + 0.02x_1x_4$$
$$-0.01x_2x_3 - 0.03x_2x_4 - 0.02x_3x_4 [HB 10/1000/30]$$

(2)

where: $x_1$ – solutioning temperature, $x_2$ – solutioning time, $x_3$ – ageing temperature, $x_4$ – ageing time. Correlation coefficient (for $\alpha = 0.05$): $R = 0.99$; $R^2 = 0.98$; corr. $R^2 = 0.96$.

Taking into account obtained values of the correlation coefficients, likewise in case of the dependence (1), the dependence (2) describes in satisfactory way an effects of heat treatment parameters on change of the hardness HB of the investigated alloy. In the Fig. 7 are presented experimental (real) and predicted values of the hardness HB of the investigated alloy.

Fig. 7. Diagram of experimental and predicted values of the hardness HB

In the Fig. 8 are shown structures of the alloy after refinement and modification.
Performed treatment of the modification resulted in change of morphology of eutectic silicon precipitations from a lamellar to a stripped ones (Fig. 8b).

Structures of the alloy after performed heat treatment operations in case of the test pieces from the system characterized by the highest value of the hardness (system no. 13 – solutioning temperature – 520°C; solutioning time – 1.5 hour; ageing temperature – 180°C; ageing time – 5 hour) are shown in the Fig. 9.

As it can be seen from the Fig. 9b, morphology of the microstructure changed obviously after the T6 heat treatment. The irregular eutectic phase was converted into fine spheroidized Si particles uniformly distributed in the Al matrix, what significantly improved the mechanical properties.

4. Conclusion

Performed T6 heat treatment has an effect on change of mechanical properties of the investigated alloy. Selection of adequate temperatures and times of solution heat treatments and ageing treatments determines growth of the tensile strength $R_m$ and hardness $H_B$.

Obtained of the highest tensile strength $R_m$ and hardness $H_B$ determines adoption of:

– ageing temperatures up to 180°C,
– ageing times from 2 to 8 hours,
– solutioning temperatures in range of 520-535°C,
– solutioning times from 0.5 to 1.5 hour.

Usage of increased temperatures of the ageing treatment has adverse effect on change of the $H_B$ hardness of the investigated alloy, resulting it its decrease.

REFERENCES

[1] M. Panušková, E. Tišlová, M. Chalupová, Strength of Materials 40, 1, 98-101 (2008).
[2] S. Kozhar, D. Regener, H. Zak, H. Altenbach, International Foundry Research/Gießereiforschung 62, 2, 26-31 (2010).
[3] F. Zupančič, T. Bončina, N. Rozman, B. Markoli, RMZ – Materials and Geoenvironment 58, 1, 1-14 (2011).
[4] J.C. Williams, E.A. Starke Jr., Acta Materialia 51, 19, 5775-5779 (2003).
[5] L.A. Dobrzanski, L. Reimann, G. Krawczyk, Archives of Materials Science and Engineering 31, 1, 37-40 (2008).
[6] B. Closset, J.E. Gruzleski, Metallurgical Transactions A 13, 6, 945-951 (1982).
[7] J.R. Davis, Aluminium and Aluminium Alloys, ASM International 1993.
[8] E. Ogris, A. Wahlen, H. Lüchinger, P.J. Uggowitzer, Journal of Light Metals 2, 4, 263-269 (2002).
[9] Z. Górny, Odelewnicze stopy metali nieżelaznych, PWN Warszawa 1992.
[10] D.K. Dwivedi, A. Sharma, T.V. Rajan, Materials and Manufacturing Processes 20, 5, 777-791 (2005).
[11] A.S.M. Handbook-Committee, ASM handbook. Heat Treating 4, American Society for Materials (1991).
[12] J.G. Kaufman, E.L. Rooy, Aluminum Alloy Castings: Properties, Processes And Applications, ASM International 2004.
[13] Z. Lech, E. Czekaj, J. Nykiel, B. Kulaga, Archiwum Odelewnictwa 2, 6, 75-90 (2002).
[14] K.V. Sudhakar, K. Konen, K. Floreen, Archives of Metallurgy and Materials 57, 3, 753-757 (2012).

[15] E. Sjölander, S. Seifeddine, Journal of Materials Processing Technology 210, 10, 1249-1259 (2010).

[16] J. Pezda, Archives of Foundry Engineering 10, 1, 131-134 (2010).

[17] P. Ouellet, F.H. Samuel, Journal of Materials Science 34, 19, 4671-4697 (1999).

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