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Effect of T6 Heat Treatment Parameters on Technological Quality of the AlSi7Mg Alloy

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Abstract

Very well-known advantages of aluminum alloys, such as low mass, good mechanical properties, corrosion resistance, machining-ability, high recycling potential and low cost are considered as a driving force for their development, i.e. implementation in new applications as early as in stage of structural design, as well as in development of new technological solutions. Mechanical and technological properties of the castings made from the 3xx.x group of alloys depend mainly on correctly performed processes of melting and casting, design of a mould and cast element, and a possible heat treatment.

The subject-matter of this paper is elaboration of a diagrams and dependencies between parameters of dispersion hardening (temperatures and times of solutioning and ageing treatments) and mechanical properties obtained after heat treatment of the 356.0 (EN AC AlSi7Mg) alloy, enabling full control of dispersion hardening process to programming and obtaining a certain technological quality of the alloy in terms of its mechanical properties after performed heat treatments. Obtained results of the investigations have enabled obtainment of a dependencies depicting effect of parameters of the solutioning and ageing treatments on the mechanical properties (R_m, A_5 and KC impact strength) of the investigated alloy. Spatial diagrams elaborated on the basis of these dependencies enable us to determine tendencies of changes of the mechanical properties of the 356.0 alloy in complete analyzed range of temperature and duration of the solutioning and ageing operations.

Keywords: Heat treatment, Aluminum alloys, Tensile strength, Elongation, Impact strength

1. Introduction

Oftentimes, producers of a cast machinery parts made from the Al-Si-Mg, Al-Si-Cu and Al-Si-Cu/Mg alloys do not take full advantage of all possibilities offered by this material, in scope of its mechanical and technological properties, justifying it by economical reasons resulted from performed heat treatment process (long time of performed operations of the solutioning and ageing) and concerns about a possible partial melting of a processed component during solutioning operation, which is usually performed at temperature close to eutectic temperature of the alloy (practically, the solutioning temperature should be lower with 20-30°C than the eutectic temperature). Moreover, the processes occurring during artificial ageing and comprising precipitation from supersaturated solution of strengthening phases, should be also performed at increased temperature (150-260 ^{o}C) for a specified period of time.

Many authors had taken efforts to investigate effects of temperature and time of heat treatment operations on change of microstructure and mechanical properties of the 356.0 casting alloy [1-3]. Likewise, the author of this paper has conducted research work from this area [4-6]. Normally, the ASTM B917-01 standard, for the 356.0 alloy specifies solutioning time of 6-12 hours at temperature 540 ^{o}C, cooling in warm water, and next 2-5 hours at temperature 155 ^{o}C, for a castings from sand mould [7]. Instead, for a castings from metal moulds, 4-12 hours of solutioning at 540 °C and 2-5 hours of ageing at temperature 155 °C [7].

The AFS proposes solutioning at 538 °C for 12 hours and ageing at 155 °C for 3-5 hours in case of sand castings, and 227 °C for a die castings [8]. Zolotorevsky [9] for the AK7 alloy reports solutioning temperature 535 °C, solutioning time 2-7 hours and ageing at temperature 150 °C for 1-3 hours. Temperature close to the solutioning (535-540 °C), but longer solutioning time (8 hours for a castings from metal moulds and 12 hours, for a castings from sand moulds) and ageing at 150-155 °C for 2-5 hours is reported by the authors of [10, 11]. Davidson in his study [12], reducing time of the solutioning from 8 to 4 hours, did not notice any effect on its fatigue strength. According to Shivkumar [13], solutioning for 3-6 hours at temperature 540 °C is optimal for modified alloy, poured to sand moulds. However, D. Emadi [14] had shown in his investigations that solutioning time of 4 hours at 540 °C assures optimal properties, while Yoshida [15] had obtained the highest hardness during short time of the solutioning (2 hours at 520 °C/540 °C and ageing at 160 °C for 6,5 hour). Pedersen [1] had obtained maximal strength as early as after 60 minutes of solutioning at 540 °C and four hours ageing at 150 °C, while prolongation of time of the treatment did not lead to increase of the strength.

Zhang in the study [16] says that solutioning for 10 minutes at 540 °C or 550 °C is sufficient to reach maximal level of magnesium and silicone, as anticipated in limits of solubility and composition of the alloy. Treatment for 30 minutes results in spheroidization and increased space between precipitations of eutectic silicone. It leads to considerable improvement of ductility and impact strength. Comparing with standard process of the solutioning for 6 hours, 30 minutes of the solutioning at temperature 540 and 550 °C is sufficient to reach more than 90 % of the $R_{0,2}$ and not more than 95 % of the R_m. Similar mechanical properties were obtained by Peng [17], however after solutioning at 550 °C for 2 hours and ageing at 170 °C also for 2 hours.

On the basis of the above results it can be ascertained that there exist a pretty big discrepancies concerning ranges of the temperature and duration of the solutioning and ageing operations, however, shortening of these durations is possible without any considerable effect on obtained mechanical properties of the 356.0 aluminum alloy.

As the main problem emerges determination of a range of temperature and time of individual operations, enabling obtainment of suitable mechanical properties of the alloy.

In the paper is presented heat treatment process of a test pieces produced from the 356.0 alloy, which was performed of the basis of specified range of the parameters aimed at obtainment of significant improvement of mechanical properties of the material, with consideration of economical aspect of the performed process (limitation of temperature and time of the solutioning and ageing operations), and are presented elaborated dependencies and spatial diagrams plotted on the basis of such dependencies, which describe effect of parameters of the solutioning and ageing treatments on the mechanical properties (R_m, A_5 and KC impact strength) of the investigated alloy, as well as depicting tendencies of changes of its mechanical properties in complete analyzed range of time and temperature of the solutioning and ageing treatments.

2. Methodology of the research

Perfect ductility, corrosion resistance and high ratio of the strength to the mass make that the 356.0 alloy from the Al-Si-Mg group is suitable to various applications within automotive industry, such as cylinder blocks and heads, wheel rims, and complex thin-wall elements produced in casting process with use of metal and sand moulds, having strength up to 350 MPa [6, 9, 18-19]. Chemical composition of the investigated alloy is presented in the Table 1.

Table 1.
Chemical composition of the 356.0 (EN AC-AlSi7Mg) alloy

Chemical composition / mass %				
Si	Cu	Zn	Fe	Mg
7,2	0,27	0,3	0,65	0,3
Ni	Mn	Pb	Cr	Al
0,1	0,27	0,02	0,07	rest

Analysis of the chemical composition was performed using an optical emission spectrometry method, with inductively coupled plasma on the PerkinElmer optical emission spectrometer, Optima 4300 Dv model, in the Bosmal R&D Institute in Bielsko-Biala.

To produce the test pieces, which were used in course of the investigations, the alloy was melted in electric resistance furnace at temperature of 720-750°C. In the next stage it has been performed refining treatment with use of refining preparation (Rafal 1), in quantity 0,4% mass of the charge. Refined alloy, after removal of oxides and slag from the metal level, was modified with the AlSr10 master alloy, in quantity of 0,5-0,6% mass of the charge. Temperature of the liquid alloy was maintained at the level of 720-740 °C.

The Al-Si casting alloys, in most cases, are the product being result of recycling. There exists, therefore, a danger connected with possibility of partial melting of heat treated machinery parts, due to presence of low melting phases and inter-metallic compounds, and changes in temperature of melting process.

A solution in such case could be the ATD method, serving to recording of crystallization course of metals and alloys. Information obtained on the basis of curves from the ATD method make possible not only to determine, with a high accuracy, melting temperature of a given alloy, but also melting temperatures present in the alloy of low melting phases. This method has enabled initial selection of range of temperatures of the solutioning and ageing operations (Fig. 1) used in assumed trivalent plan of the investigations with four variables.

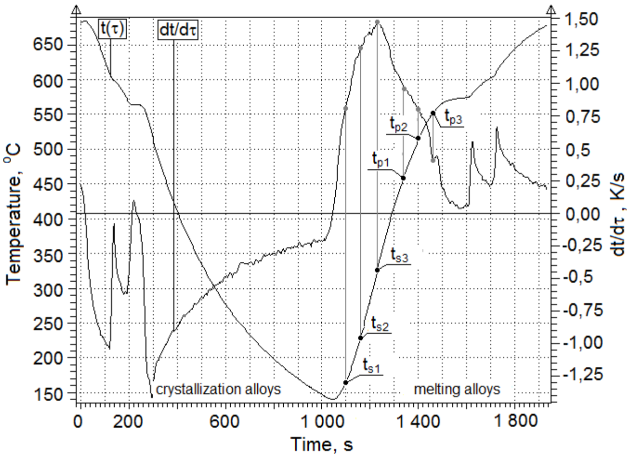

Fig. 1. ATD diagram of the investigated alloy

On curves from the ATD method (Fig. 1) are marked characteristic points having values denoting temperatures of the solutioning and ageing operations, implemented in the assumed plan of the investigations. In the Table 2 are presented parameters of solutioning and ageing for performed heat treatment operation of the investigated alloy.

Table 2.
Heat treatment parameters of the 356.0 alloy

solutioning temperature t_p, °C	solutioning time τ_p, h	ageing temperature t_s, °C	ageing time τ_s, h
t_{p1} - 465	0,5	t_{s1} - 165	2
t_{p2} - 520	1,5	t_{s1} - 235	5
t_{p3} - 550	3	t_{s1} - 325	8

Standardized test pieces were poured in a mould produced according with the PN-88/H-88002 standard, while the test pieces to impact test were poured in a mould produced for simplified impact test [20]. The heat treatment consisted of solutioning, followed by rapid cooling of the test pieces in water at temperature 20 °C and artificial ageing with cooling at the air.

Solutioning operations were performed in a resistance furnace. Measurement of the temperature was performed continuously with use of Ni-NiCr thermoelements of type K, with accuracy ± 5°C directly in chamber of the furnace.

After performed heat treatment, the test pieces to measurement of the tensile strength R_m and elongation A_5 were prepared according with the PN-EN ISO 6892-1:2010P standard (the test piece with measuring length of 50 mm and diameter of 10 mm). Static tensile tests were performed according with the PN-EN ISO 6892-1:2010P standard, on the strength tester of the ZD-20 type. Measurement of the Brinell hardness was performed according to the PN-EN ISO 6506-1:2008P standard, with use of the Brinell hardness tester of the PRL 82 type, with steel ball having 10 mm diameter, under load 9800 N, sustained for 30 seconds. The hardness of the poured test pieces was measured on grip sections of milled test pieces to the strength tests.

Determination of the impact strength of casting alloys was made basing on the simplified method [20], with use of the Charpy pendulum machine, with use of the test pieces having incised cylindrical notch.

In such case, the impact strength denotes ratio of the work used to rupture of the test piece (in J) to surface area of cross section in place of the notch (in cm^2). Obtained in such way results can not be compared with results of the standardized tests [20].

The software package "Statistica" ver. 10 of the StatSoft Company was used to obtain the dependencies and plot the diagrams showing effect of the heat treatment parameters on the mechanical properties of the investigated alloys

3. Description of obtained results

3.1. Tensile strength R_m

Tensile strength of the raw alloy (from pig sows) amounted to 190 MPa. After refinement there occurred a slight change (199 MPa), while performed treatment of modification has enabled obtainment of the R_m within limits 200-205 MPa.

After performed heat treatment of the alloy, obtained tensile strength R_m amounted from 154 to 335 MPa.

Making comparison of obtained values of the R_m strength for the alloy after heat treatment and without the heat treatment (Fig. 2) it has been ascertained the highest increase of the R_m strength for the systems: 13 (t_p= 520 °C; τ_p= 1,5 hour; t_s= 165 °C; τ_s= 5 hours), system 19 (t_p= 550 °C; τ_p= 0,5 hour; t_s= 165 °C; τ_s= 5 hours) and the system 25 (t_p= 550 °C; τ_p= 3 hours; t_s= 165 °C; τ_s= 8 hours). Slightly lower tensile strength, within limits of 300 MPa, was obtained for the systems 4, 16 and 22 characteristic of, similarly like in case of the systems 13, 19 and 25, with low ageing temperature (t_s= 165 °C) during 2 to 8 hours.

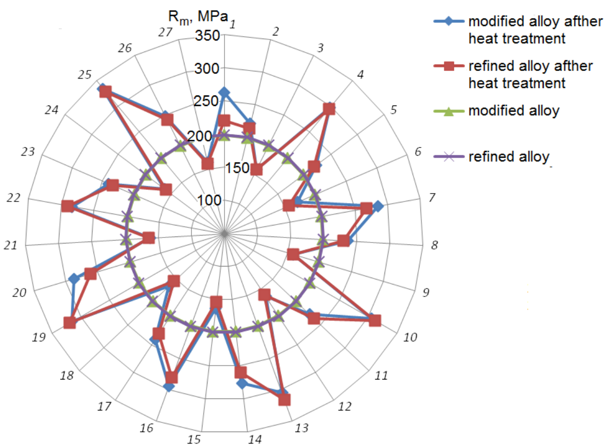

Fig. 2. Tensile strength R_m of the investigated alloy

The lowest tensile strength R_m was obtained for the systems 3, 9 and 27, which were characteristic of high ageing temperature (t_s= 325 °C), in complete range of ageing times. Obtained value of the R_m for these systems amounting to 158-163 MPa constitutes its distinct decrease with respect to the alloy without the heat treatment. Results of performed investigations have enabled development of dependencies (1), in form of second order polynomial, describing effect of the heat treatment parameters on change of the R_m strength of the investigated alloy.

$$R_m = -64{,}66 + 0{,}738 t_p + 2{,}53\cdot 10^{-4} t_p^2 + 60{,}855\tau_p - 0{,}844\tau_p^2 + 0{,}655 t_s - 2{,}41\cdot 10^{-4} t_s^2 + 7{,}64\tau_s + 0{,}364\tau_s^2 - 0{,}105 t_p\tau_p - 22{,}68\cdot 10^{-4} t_p t_s - 0{,}007 t_p\tau_s - 0{,}027\tau_p t_s + 0{,}805\tau_p\tau_s - 0{,}036 t_s\tau_s \quad (1)$$

where: t_p – solutioning temperature, τ_p – solutioning time, t_s – ageing temperature, τ_s – ageing time. Coefficients of: correlation R = 0,99; determination R^2=0,98; correction. R^2=0,95.

Effect of temperature and time of the solutioning and ageing operations of performed heat treatment operations on change of the tensile strength R_m, is presented in graphical form on spatial diagrams (Fig. 3). For the solutioning operation it has been taken constant values of the ageing parameters: temperature t_s= 165 ^oC and time τ_s= 5 hours, while for the operation of the ageing, fixed parameters of the solutioning operation are: temperature t_p= 520 ^oC and time τ_s= 1 hour.

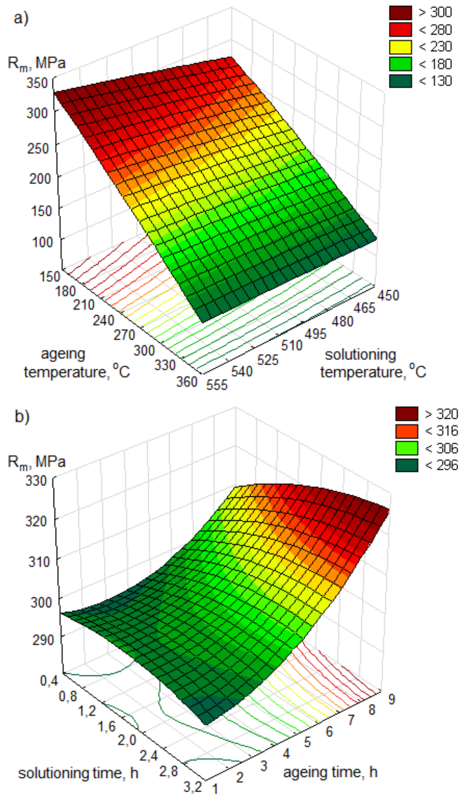

Fig. 3. Effect of parameters of the solutioning and ageing operations on the tensile strength R_m: a) t_s and t_p, b) τ_p and τ_s

Obtainment of maximal increase of the tensile strength R_m of the alloy is possible after its solutioning at temperature t_p= 520-550 ^oC for 1 to 3 hours, and next, cooling in cold water and ageing for 5 to 8 hours at temperature t_s= 165 ^oC.

3.2. Elongation A_5

Value of the elongation A_5, obtained for the raw alloy (from pig sows), amounted to 5,4 %. After refinement there occurred a slight change of the elongation (5,7 %). Performed treatment of modification of the investigated alloy has enabled obtainment of the elongation A_5 = 6,5 %, whereas performed heat treatment resulted in change of the elongation A_5 within range of 3,7 to 15,6 %.

Making comparison of obtained values of the elongation A_5 for the alloy after heat treatment and the alloy without the heat treatment (Fig. 4), it has been ascertained the highest increase of the elongation A_5 for the system 9 (solutioning temperature - t_p= 465 ^oC; solutioning time - τ_p= 0,5 hour; ageing temperature - t_s= 325 ^oC; ageing time - τ_s= 8 hours), system 15 (t_p= 520 ^oC; τ_p= 1,5 hour; t_s= 325 ^oC; τ_s= 8 hours) and system 24 (t_p= 550 ^oC; τ_p= 1,5 hour; t_s= 325 ^oC; τ_s= 5 hours). The smallest elongation A_5 was obtained for the test pieces from the systems 4, 7 and 10, characteristic of low ageing temperature (t_s= 165 ^oC), during 5 to 8 hours. Obtained elongation A_5 for these systems, comparing with the input alloy (without the heat treatment), is smaller with 30-40%.

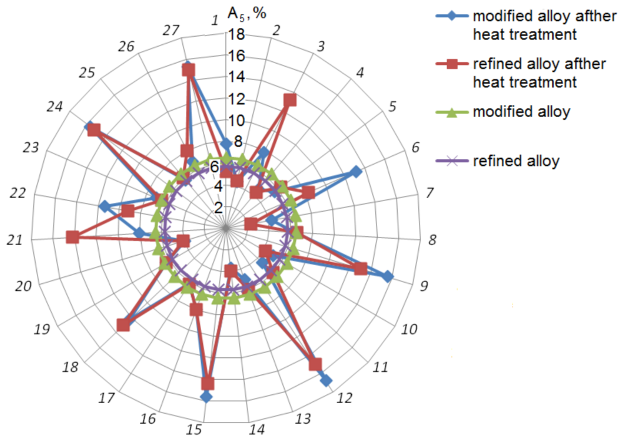

Fig. 4. Elongation A_5 of the 356.0 alloy

Obtained results have enabled development of the dependencies (2) in form of second order polynomial, describing effect of heat treatment parameters on change of the elongation A_5 of the investigated alloy.

$$A_5 = 234{,}75 - 0{,}789 t_p + 7{,}94\cdot 10^{-4} t_p^2 - 1{,}436\tau_p - 0{,}382\tau_p^2 - 0{,}269 t_s + 5{,}83\cdot 10^{-4} t_s^2 - 2{,}107\tau_s - 0{,}087\tau_s^2 + 0{,}002 t_p\tau_p - 0{,}17\cdot 10^{-4} t_p t_s + 0{,}0003 t_p\tau_s + 0{,}009\tau_p t_s + 0{,}012\tau_p\tau_s + 0{,}003 t_s\tau_s \quad (2)$$

where: t_p - solutioning temperature, τ_p - solutioning time, t_s - ageing temperature, τ_s - ageing time. Coefficients of: correlation R = 0,97; determination R^2=0,94; correction. R^2=0,87.

In the Fig. 5 is presented effect of temperature and time of the solutioning and ageing operations on change of the elongation A_5 of the investigated alloy at constant parameters of the ageing (t_s= 165 ^oC and τ_s= 5 hours) in case of the solutioning, and constant parameters of the solutioning (t_p= 520 °C and τ_p= 1 hour) for the operation of ageing.

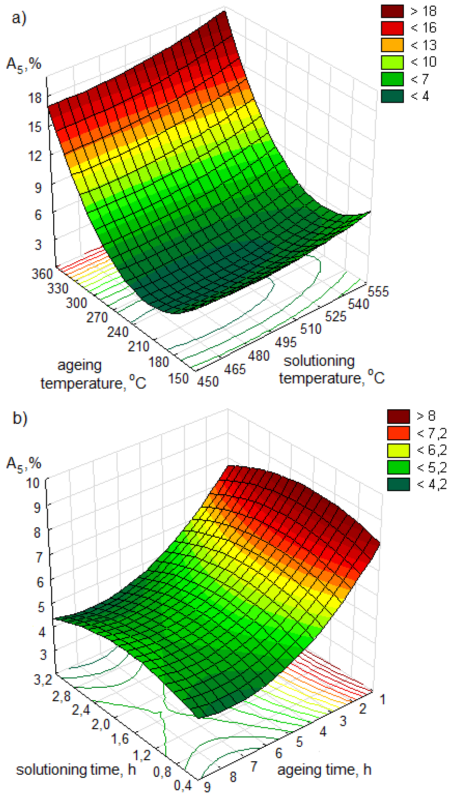

Fig. 5. Effect of the solutioning and ageing parameters on the elongation A_5 of the 356.0 alloy: a) t_s and t_p, b) τ_p and τ_s

3.3. Impact strength KC

Impact strength of the raw alloy (from pig sows) amounted to 5,4 J/cm². After refinement had occurred a slight change of the impact strength - 5,7 J/cm². Performed treatment of modification of the investigated alloy did not have any considerable effect on change of the impact strength, which was included within range of 5,8 to 6,2 J/cm². Impact strength of modified alloy after the heat treatment was changing within range from 4,2 to 27,5 J/cm².

Making comparison of obtained values of the impact strength of the alloy after the heat treatment and the alloy without the heat treatment (Fig. 6), it has been confirmed that the biggest increase of the impact strength is seen for the following systems: system 18 (solutioning temperature - t_p= 520 °C; solutioning time - τ_p= 3 hours; ageing temperature - t_s= 325 °C; ageing time - τ_s= 2 hours) and the system 27 (t_p= 550 °C; τ_p= 3 hours; t_s= 325 °C; τ_s= 2 hours). The lowest impact strength was obtained for the test pieces from the systems 10 and 25, characteristic of low ageing temperature (t_s= 165 °C) during 8 hours.

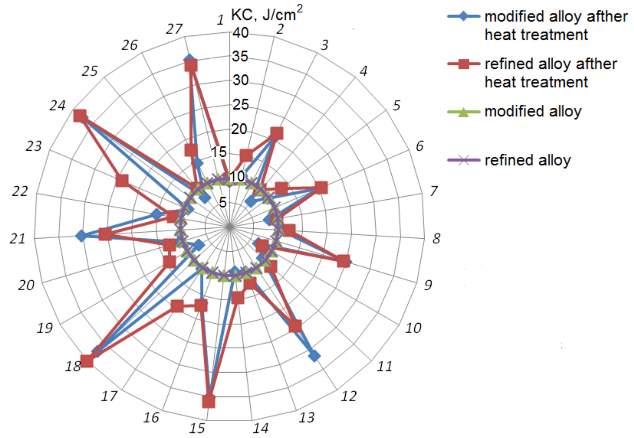

Fig. 6. Impact strength KC of the 356.0 alloy

Results of the performed investigations have enabled elaboration of the dependencies (3) in form of second order polynomial, describing effect of the heat treatment parameters on change of the impact strength KC of the investigated alloy.

$$KC = -16{,}596 + 0{,}335t_p - 4{,}44\cdot10^{-4}t_p^2 + 4{,}492\tau_p - 0{,}308\tau_p^2 - 0{,}66t_s$$
$$+ 8{,}73\cdot10^{-4}t_s^2 + 1{,}088\tau_s - 0{,}060\tau_s^2 - 0{,}012t_p\tau_p + 6{,}03\cdot10^{-4}t_pt_s \qquad (3)$$
$$+ 0{,}001t_p\tau_s + 0{,}004\tau_pt_s - 0{,}173\tau_p\tau_s + 0{,}002t_s\tau_s$$

where: t_p - solutioning temperature, τ_p - solutioning time, t_s - ageing temperature, τ_s - ageing time. Coefficients of: correlation R = 0,98; determination R^2=0,97; correction. R^2=0,93.

In the Figs. 7-8 is presented effect of temperature and time of the solutioning operation on change of the impact strength of the investigated alloy at constant parameters of the ageing (t_s= 165 °C and τ_s= 5 hours), as well as effect of temperature and time of the ageing on change of the impact strength of the alloy at constant parameters of the solutioning (t_p= 520 °C i τ_p= 1 hour).

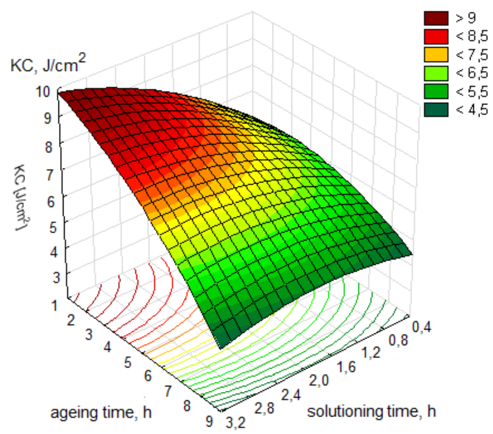

Fig. 7. Effect of time of the solutioning and ageing on the impact strength KC of the 356.0 alloy

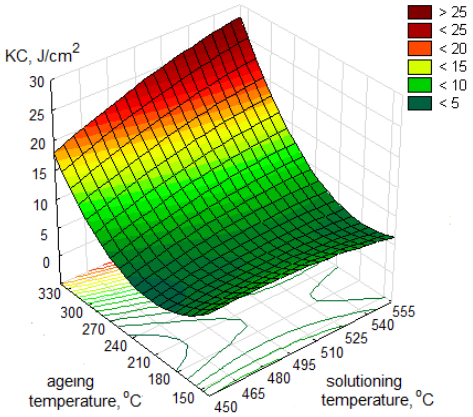

Fig. 8. Effect of temperature of the solutioning and ageing on the impact strength KC of the 356.0 alloy

The highest value of the impact strength was obtained for the test pieces solutioned at temperature t_p= 520-550 ^oC, for 1,5 to 3 hours, cooled in water, and next aged at temperature t_s above 300 ^oC, for 2 to 5 hours. Ageing temperature within limits of 160-240 ^oC have an adverse effect on the impact strength of the 356.0 alloy, resulting in its decrease comparing to the alloy without the heat treatment.

4. Conclusions

Developed methodology of the investigations, concerning heat treatment of the commercial 356.0 (AlSi7Mg) alloy has enabled determination (selection) of the solutioning and ageing parameters, assuring considerable improvement of their mechanical properties.

Obtained results of the investigations have enabled obtainment of the dependencies describing effect of the solutioning and the ageing parameters on the mechanical properties (R_m, A_5, and impact strength KC) for the 356.0 alloy. Spatial diagrams plotted on their basis enable determination of a trends of changes of its mechanical properties in complete analyzed range of time and temperature of the solutioning and the ageing treatments.

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