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Determining the optimal solution treatment temperature of aluminum cast alloys by using quantitative analysis

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Abstract: Heat treatment of aluminum casts is necessary for achieving the desired properties of casts. Heat treatment caused changes in microstructure and substructure of materials and therefore it is necessary to control which changes are sufficient and which are insufficient. Morphology (shape, size and distribution) of microstructural features influence the properties of cast rapidly. Contribution describes influence of the heat treatment marking T4 - solution treatment in dependence on temperature (505, 515 a 525 °C) and holding time (2, 4, 8, 16 a 32 hour) on structure (α –phase, eutectic silicon, intermetallic phases) and mechanical properties (ultimate tensile strength - UTS and Brinell hardness - HBW) of A226 cast alloy. This cast alloy is made out of secondary aluminum. Secondary aluminum alloys are made of aluminum scrap. About 70 % of such material are used in the manufacture of casts. Therefore the strictly microstructure control of experimental material before and after heat treatment is necessary for declaration of cast properties. Nowadays manufacturers use the methods of quantitative analysis for quick control of microstructural features. This work present some of them.

Key words: aluminum cast alloys, quantitative analysis, microstructural features, eutectic Si, Fe-rich phases, Cu-rich phases.

1. Introduction

The aluminum alloys are now used much more than any other construction material such as steel, magnesium, copper, etc.. Thanks to better mechanical properties: impact energy, ductility, cheaper extrusion, casting of complex components, better noise reduction, better corrosion resistance are aluminum alloys the major material for automotive and aerospace industry applications. The nowadays casting and heat treatment possibilities lead to producing casts from materials groups Al-Si-Cu and Al-Si –Mg in order to reach sufficient properties of casting products for industry applications [1]. Such material found their application in engine cooling fans, crank cases, high speed rotating parts, structural aerospace components, air compressor pistons, fuel pumps, compressor cases, timing gears, rocker arms, machine parts, etc. due to its excellent castability, good mechanical properties and cost-effectiveness [2-8].

For the optimal use and control of aluminum alloys, it is necessary to quantify not only their properties (these are expressed in numerical values), but also the microstructure. The typical microstructural features which influence the aluminum alloy properties are α-phase (dendrite arm spacing), eutectic Si particles morphology, secondary phases (size, shape and distribution) and casting defects (place where they are, size, shape and distribution) [9].

Quantitative metallography includes methods of quantification of microstructural features (evaluation by standards, structural parameter measurement, and automatic image analysis). These methods offers measuring linear and area dimensions of microstructural features which are important for prediction the properties of casts [10].

The study is part of large research projects focused on the quantification of selected microstructural features (α-phase, eutectic silicon, intermetallic phase) of aluminum alloys made from secondary aluminum, depending on temperature of solution treatment 505, 515 and 525 ° C with holding times 2, 4, 8, 16 and 32 hours and natural aging 24 hours at room temperature (20 °C ± 2 °C). Basis on the quantitative analysis results determine the optimal solution treatment for casts from such material.

2. Experimental material and procedure

This work relies on the comparison of the microstructural features evaluation present on metallographic micrographs of A226 cast alloy (Table 1). The investigations include an analysis of different temperature and holding time influence on microstructural features morphology. The experimental material was delivered as secondary, therefore have a higher amount of Fe (Table 1).

Table 1 Chemical composition of AlSi9Cu3 cast alloy, wt. %

Si	*Cu*	*Mn*	*Zn*	*Mg*	*Fe*
9.4	*2.4*	*0.24*	*1.0*	*0.28*	*0.9*
Ni	***Ti***	***Sn***	***Pb***	***Al***	
0.05	*0.04*	*0.03*	*0.09*	*remainder*	

Whereas this materials is from group Al-Si-Cu and belongs to hypoeutectic the typical microstructural features are: matrix - dendrites α-phase, eutectic (mechanical mixture of eutectic Si and α-phase), intermetallic Fe- and Cu-rich phases and porosity (Fig. 1). The influence of the solution treatment temperature and holding time on the microstructural features morphology and amount was investigated using computer image analysis NIS Elements. The samples were for investigation prepared with standard metallographic procedures (wet ground on SiC papers, DP polished with 3 µm diamond pastes followed by Struers Op-S and etched for study under-an optical microscope by standard etcher Dix-Keller (Si particles and α-phase), H_2SO_4 (Fe rich phases) and HNO_3 (Cu rich phases)). Prepared samples were evaluated with using NEOPHOT 32 and for this analysis about 250 images of metallographic samples was used.

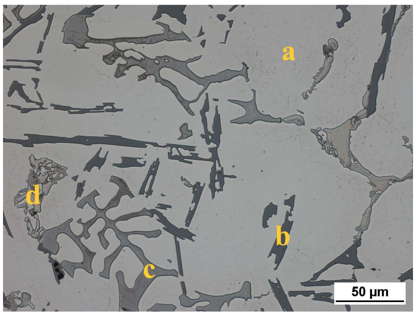

Fig. 1. The metallographic micrographs of A226 cast alloy, etch. Dix-Keller.

a) α-phase; b) eutectic Si particles; c) Fe-rich phases; d) Cu-rich phases

Mechanical properties were measured according to the standards: STN EN ISO 6892-1:2010 and STN EN ISO 6506-1 [11-12]. The experimental tensile and hardness specimens for experimental procedure were made from the casting with turning and milling operations. Hardness measurement for secondary aluminum alloy was performed using a Brinell hardness tester with a load of 62.5 Kp, 2.5 mm diameter ball and a dwell time of 15s. The evaluated Brinell hardness reflects average values of at least six separate measurements. Tensile strength (UTS) was measured using ZDM 30 testing machine. The evaluated UTS, Ductility and HBW reflect average values of at least six separate specimens.

3. Results and discussion

Most of the recommended heat treatment of alloys that contain copper restricts the solution temperature below the final solidification point in order to avoid the melting of copper-rich phases. Solution treatment performs tree roles: homogenization of as-cast structure; dissolution of certain intermetallic phases such as Al_2Cu; changes the morphology of eutectic Si phase by fragmentation, spheroidization and coarsening, thereby improving mechanical properties, particularly ductility [13].

The effect of solution treatment on morphology of eutectic Si is demonstrated in Figure 2. The changes of morphology eutectic Si observed after heat treatment T4 are documented for holding time 4 hours. This temperature was optimal in terms of mechanical properties. Eutectic Si without heat treatment (as cast state) occurs in long needles form (Figure 2a). After solution treatment at temperature 505 °C were noted that the long needles were fragmentized into smaller needles with spherical edges (Figure 2b). The spheroidized process dominated at 515 °C. The smaller Si particles were spheroidized to rounded shape, see Figure 2c. With increasing temperature of solution treatment (525 °C) the spheroidized particles gradually grew larger (coarsening) (Figure 2d).

The results of quantitative methods shows that average size of eutectic Si particles decreases with increasing solution temperature and during the whole solution period (Figure 3). Minimum value of average eutectic Si particles was observed by temperature 515°C (89 μm^2). It's probably context with spheroidization of eutectic silicon on this temperature. The average volume of Si particles in microstructure was about 8 % in as cast state and about 7,5 % in sate after each heat treatments.

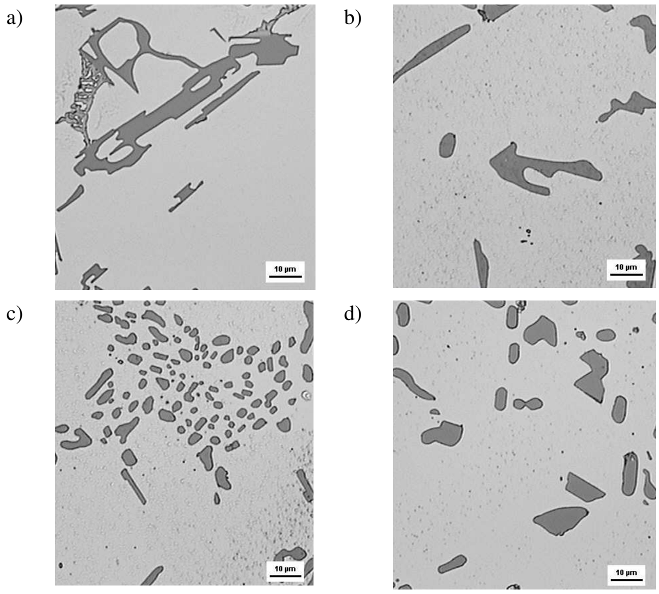

Fig. 2. Morphology changes of eutectic Si in experimental material during heat treatment T4.

a) as-cast state; b) 505 °C / 4 h.; c) 515 °C / 4 h.; d) 525 °C, 4 h.

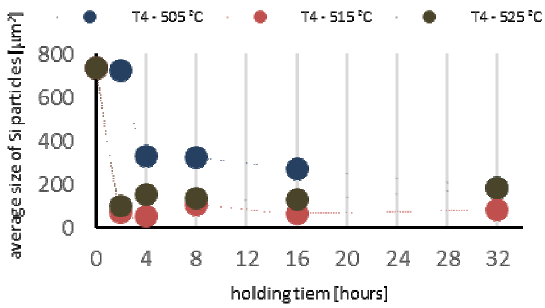

Fig.3. Quantitative results of average size of Si particles during heat treatment.

In this cast alloy were encountered Fe-rich phases with cubic crystal structure $Al_{15}(FeMnMg)_3Si_2$. The effect of solution treatment on the $Al_{15}(FeMn)_3Si_2$ phase for solution time 4 hours is described on Figure 4. These phases was in form compact skeleton – like in as-cast state of material (Figure 4a). Solution treatment of this skeleton-like phase at 505 °C tends to fragmentation (Figure 4b) and at 515 or 525 °C also to segmentation (Figure 4c, 4d).

Quantitative analysis shows that solution treatment reduces size of these phases rather than change the morphology (Fig. 5). Figure 4 shows the volume of phase $Al_{15}(FeMn)_3Si_2$ obtained in solution heat treated samples, calculated as a percentage of the average value. A maximum value of surface fraction = volume of Fe-rich phase was observed at temperature 505 °C (4.3 %) and minimum value was observed at temperature 515 °C (1.3 %). This quantitative analysis are important because the volume of Fe-rich phases influence to ductility.

Figure 6 shows the average size of $Al_{15}(FeMn)_3Si_2$ phases obtained in solution heat treated samples. Maximum value of average size of Fe-rich phases was observed at temperature 505 °C (732 μm^2) and minimum average size was observed at temperature 515 °C (322 μm^2). The assessment of average size of Fe-rich phases is important, because influence the tensile strength. With increasing size of Fe-rich phases decreasing the properties of aluminum casts.

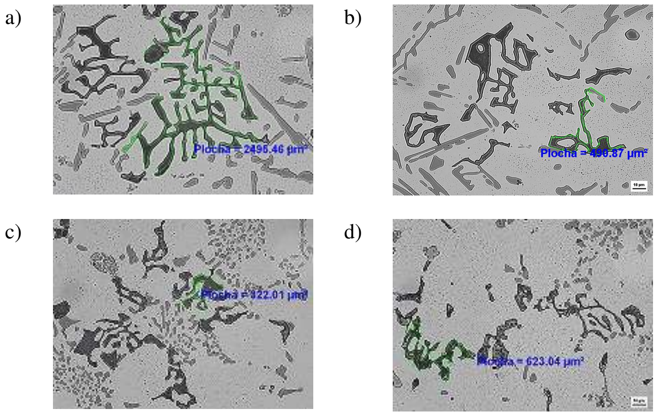

Fig. 4. Quantitative evaluation of average size of Fe-rich phases in experimental material, etch. H_2SO_4, 500x.

a) as-cast state; b) 505 °C / 4 h.; c) 515 °C / 4 h.; d) 525 °C, 4 h.

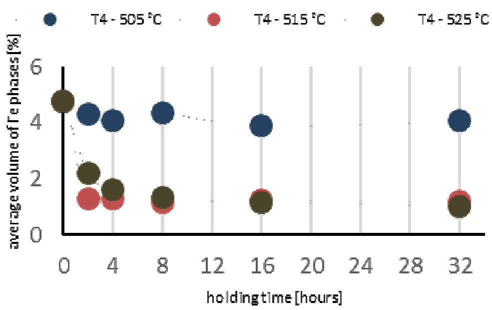

Fig.5. Quantitative results of average volume of Fe-rich phases during heat treatment.

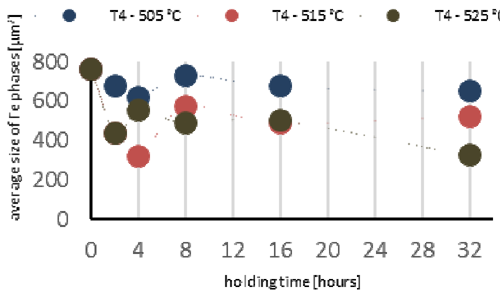

Fig. 6. Quantitative results of average size of Fe-rich phases during heat treatment.

Effect of solution treatment on morphology of Al-Al_2Cu-Si is demonstrated on Figure 4. Al-Al_2Cu-Si phase in as cast state occurs in form compact oval troops (Figure 7a). After solution treatment at temperature 505 °C these phase disintegrated into fine smaller segments and the amount of Al-Al_2Cu-Si phase during heat treatment decreases (Figure 8, Figure 7b). At 515 °C is this phase observed in the form coarsened globular particles and these occurs along the needles, probably Fe-rich (Al_5FeSi) phase (Figure 7c) [7]. With increasing temperature of solution treatment (525 °C) is this phase documented in the form molten particles with homogenous shape, because this temperature is very high with respects to the Cu-rich phases (Figure 7d) [8]. The dissolution rate of intermetallic compounds is temperature sensitive and even a 10 °C increase in temperature has an appreciable effect on optimum solution times and on mechanical properties.

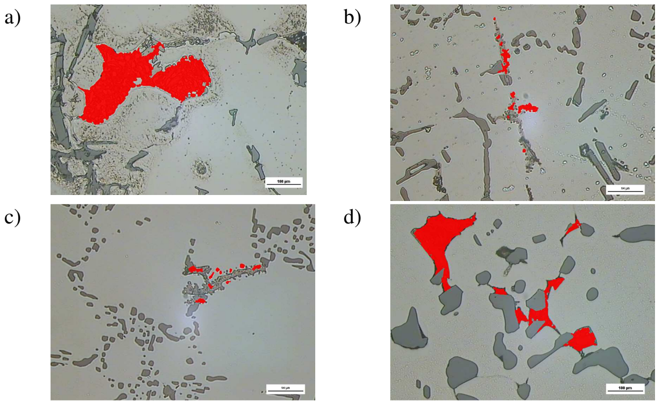

Fig. 7. Quantitative evaluation of average volume of Cu-rich phases in experimental material, etch. HNO_3, 500x.

a) as-cast state; b) 505 °C / 4 h.; c) 515 °C / 4 h.; d) 525 °C, 4 h.

The average volume of Cu-rich phases in experimental materials decrease up to 515 °C, but at temperature 525 °C the volume again increase in order to changes morphology of these phases (Figure 8).

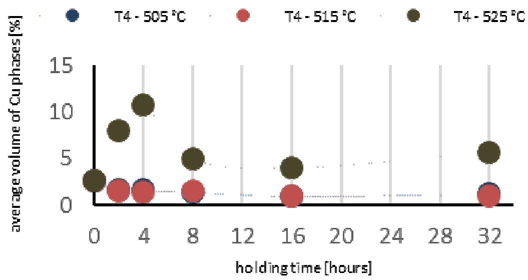

Fig.8. Quantitative results of average volume of Cu-rich phases during heat treatment.

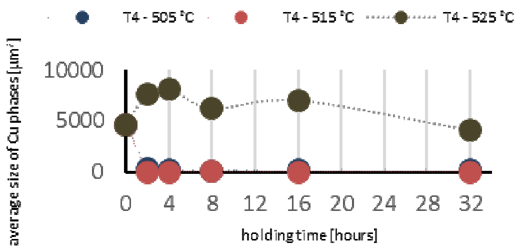

Fig.9. Quantitative results of average size of Cu-rich phases during heat treatment.

Diagram 5 shows the average size of Al-Al_2Cu-Si phases obtained in solution heat treated samples. It is evident that heating at temperatures below the final solidification temperature (505°C, 515°C and 525°C) results in a dissolution of Al-Al_2Cu-Si phase. Dissolution is accelerated as soon as the holding time is increased to 4 hours, where the dissolution exhibits a relatively linear behavior with holding time. Further heating does not bring about much change in the volume or size of Al-Al_2Cu-Si phase. Maximum average size of Al-Al_2Cu-Si phases was observed at 525 °C with holding times 2 hours (9 995.5 μm^2). Minimum average size of Al-Al_2Cu-Si phases was observed at 515 °C (0.277 μm^2).

Influence of solution treatment on mechanical properties (strength tensile – R_m and Brinell hardness - HBW) for recycled AlSi9Cu3 cast alloy is shows in Figure 10 and 11. After solution treatment, tensile strength and hardness are remarkably improved, compared to the corresponding as-cast condition. Highest strength tensile was 273 MPa for 515 °C / 4 hours. With further increase in solution temperature more than 515 °C and solution time more than 8 hours, tensile strength gently decreases during the whole solution period. This suggests that, to enhance the tensile strength of this alloy by increasing of solution temperature more than 515°C and by extending the solution time does not seem possible. Results of hardness (Figure 10) are comparable with results of tensile strength. Highest hardness was 124 HBW for 515 °C/4 hours. At 525 °C, test bars show hardness strong reduction due to melting of the Al-Al_2Cu-Si phase.

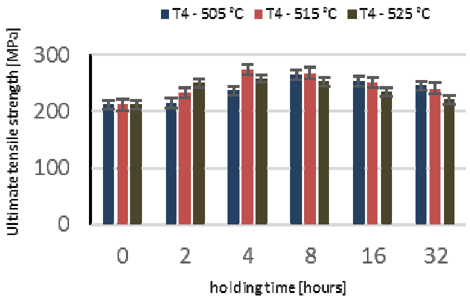

Fig. 10. Influence of solution treatment on to tensile strength

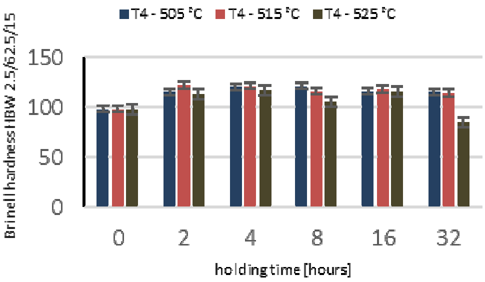

Fig. 11. Influence of solution treatment on to Brinell hardness

9. Summary and conclusions

In the present study, the effects of solution temperature and holding time on recycled AlSi9Cu3 cast alloy was investigated.

The effect of solution treatment was evaluated on samples after mechanical test with using image analysis software for declaration of the microstructural features morphology effects on mechanical properties. Results of mechanical properties (UTS, HBW) shows that experimental material have optimum value of mechanical properties at temperature 515 °C with holding time 4 hours.

The result also shows that morphology changes of microstructural features (eutectic Si particles, Cu-rich and Fe-rich phases) have a great influence on to changes of mechanical properties.

Si particles were gradually spheroidized and optimum size and volume have at 515 °C of solution treatment.

Fe rich phases were fragmented and segmented in to smaller skeleton-like particles. The optimum volume and size have at 515 °C, too.

Cu-rich phases were affected mostly with using solution heat treatment, because temperature 505 and 515 °C lead to dissolution and were optimum with respect to size and volume these phases. Temperature 525 °C was not optimal, because lead to melting the Cu-phases. This temperature is very high for solution treatment such material.

The results of quantitative analysis declaration that optimum solution treatment is at 515 °C with holding time 4 hours with respects minimum volume and size of microstructural features and highest mechanical properties.

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