DESIGN OF A NEW CASTING ALLOYS CONTAINING Li OR Ti+Zr AND OPTIMIZATION OF ITS HEAT TREATMENT

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Abstract

In this paper was proposed to design new casting alloys on the base of the Al-Mg-Si system using Li addition to achieve precipitation strengthening effect and alloying by Ti+Zr to achieve saturation of solid solution and grain refinement effect. The as-cast and heat treated structure of permanent mould casting of AlMg5Si2Mn containing 1.0 wt.% Li and 0.1 wt.% Ti + 0.1 wt.% Zr alloys was investigated by differential scanning calorimetry, microhardness measurements, scanning and transmission electron microscopy and energy dispersive X-ray analysis. Mechanical properties of these alloys were investigated with modern automated ball indentation method. This method showed good convergence with standard tensile tests and allows to determine hardness, yield stress and elastic modulus of tested alloys. It was observed that addition of Li causes modification of (Al)+(Mg_2Si) eutectic lamellas making them thinner and interlamella distance becomes larger. Ti+Zr addition does not change eutectic morphology but strongly reduces the size of α-Al dendrites, also, it produces the nucleation particles for primary Mg_2Si crystals. Homogenization of studied alloys at 570 °C results in disintegration of Mg_2Si lamellas and this process takes 30 min to transform plate like lamellas to fine spheres. It was established that hardness and microhardness both of Li and Ti+Zr containing alloys decrease at the same time. Further heating does not produce remarkable changes of hardness. Artificial aging leads to the increasing of hardness and microhardness. Obtained results showed that heat treatment of AlMg5Si2Mn improves its mechanical properties with Li and Ti+Zr assist precipitation hardening and solid solution strengthening effects.

Keywords: Aluminum, casting alloys, eutectic, microstructure, automated ball indentation, elastic modulus

1. INTRODUCTION

Automotive and aerospace industries from year to year are strongly interested in development of new alloys for production of light weight constructions. In this context alloys of the Al-Mg-Si system are considered as promising candidate for production of sheets and extruded parts using wrought alloys (6061, 6005, etc) and thin wall casting using AlMg5Si2Mn alloy. Today is established that Al-Mg-Si casting alloys possesses good corrosion resistance, weldability, high surface finishing and, in particular, good mechanical properties.

Considering additional alloying and heat treatment of AlMg5Si2Mn the data on the possibility to improve mechanical properties by alloying with Cu, Zn, Cr, Ti, Zr, Sc+Zr, Li, and heat treatment is rather limited and controversial [1-4]. According to Lenczowski [1] AlMg3Si1 containing Sc+Zr in T5 state shows ultimate tensile strength (UTS) of 270 MPa at room temperature and 265 MPa at 250 °C. From the work of Petkow et al. [2] can be seen that the AlMg5Si2Mn alloy, cast into permanent mold, shows only a slight increase of tensile and ultimate tensile strength after T6 treatment together with a dramatically low fracture elongation of about 2.5 % for temper F, decreasing down to 1.4 % after artificial aging.

Author's data and literature information, such as [5] show that the UTS of commercial A356 T6 may reach a level up to 300 MPa and an elongation to fracture of 6.0 %. Comparable to A356 is the permanent mold cast

AlMg5Si2Mn [6], where the ultimate tensile strength varies from 255 to 298 MPa and the elongation is in the range between 1.2 and 3.2 %. The elongation is one order lower than that of AlMg5Si2Mn + 0.2 wt.% Ti alloy subjected to high pressure die casting (HPDC), where it can reach 15 % [3] in as-cast state.

It is known that Al-Mg-Si belong to the group of age hardenable alloys and can be heat treated to achieve necessary combination of properties especially. However, the optimal solution treatment temperature and time as well as temperature and time for artificial aging are not established yet.

Similarly to heat treatment the effect of additional alloying of AlMg5Si2Mn alloy by, for example, Li or Ti + Zr, on the structure formation and properties are not yet satisfactory considered. From the early work of Fridlyander et al. [7] it is clear that addition of Li to Al-Cu or Al-Mg alloys can significantly enhance their properties simultaneously with decreasing density.

Last years showed strong advance in development of Al-Cu-Li and Al-Mg-Li wrought alloys. But, there is no one Li-containing casting alloy is designed yet. It was proposed to use AlMg5Si2Mn casting alloy as the base material to design Li-containing casting alloy. The idea is based on the composition of α-Al solid solution in AlMg5Si2Mn alloy which consists of 2.4 wt.% Mg, (0.3 - 0.4) wt.% Mn and no Si was detected. Subsequently, the solution grain would be similar to Al-Mg alloy and addition of Li may enhance mechanical properties of the material.

Thus, the purpose of the present paper is to establish the effect of Li and Ti + Zr additions on the microstructure and mechanical properties of Al-Mg-Si-Mn casting alloy in as cast state and after heat treatment.

1. MATERIALS AND METHODS

The chemical compositions evaluated alloys are represented in **Table 1**. As base was chosen alloy Al5Mg2Si0.6Mn (denoted H).

Table 1 Nominal composition of alloys

Alloy	Elements content, wt.% (Al - bal.)					
	Mg	**Si**	**Mn**	**Li**	**Ti**	**Zr**
H	5.0	2.0	0.6	-	-	-
L	5.0	2.0	0.6	1.0	-	-
T	5.0	2.0	0.6	-	0.1	0.1

All alloys were prepared in electric resistant furnace using graphite crucibles. As master alloys AlMg50, AlSi25, AlMn26, AlLi5, AlZr10, AlTi6 and high purity aluminum (A99.997) were used. The melt with the temperature (720 ± 5) °C had been degassing under argon atmosphere for 10 minutes.

Two types of heat treatment were applied. The first type was the solution treatment, which had been put in an electrical resistance furnace. After solution treatment, the specimens were quenched in to the water with room temperature. The second type of heat treatment is T6, which combines solution treatment at 570 °C (30 min, 1 h and 1.5 hours), quenching in water with room temperature and artificial aging. Artificial aging was conducted in a forced circulation air furnace at 175 °C for different times.

Hardness measured by a Brinell hardness testing machine (HB) with a ball diameter of 2.5 mm and a load of 62.5 kg, time of loading was 10 sec. Microhardness tests were carried out on polished non-etched specimens on a Duramin-2 microhardness tester, HV0.05 with standard indentation time.

Tensile tests were carried out using testing machine (INSTRON 5582, USA), according to the standard ČSN EN ISO 6892-1. Tensile samples were also prepared according to this standard.

Indentation tests were carried out by a special device, which due to its design is capable of continuous recording of load and indentation depth of the used indenter. Maximum load indentation was 2.5 kN. Plane-parallel samples were used for ABI (Automatic Ball Indentation) testing.

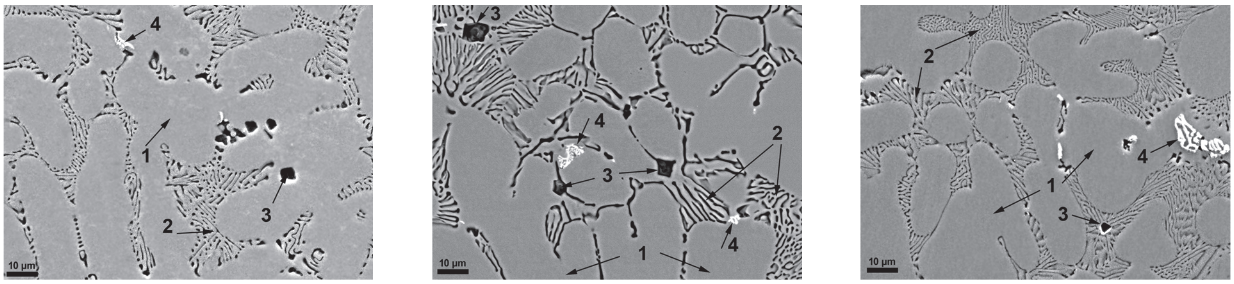
2. RESULTS AND DISCUSSION

2.1 Microstructure investigation

The structures of the base alloy and after alloying by Li and (Ti+Zr), are shown in **Fig. 1**. All alloys exhibit equiaxed grain structure and four phase constituents can be distinguished, such as:

- α-Al solid solution (gray, denoted 1);
- (Al)+(Mg_2Si) eutectic (dark, denoted 2);
- Mg_2Si primary crystals (dark, denoted 3);
- Al(Mn,Fe)Si phase (white, denoted 4).

The preferential morphology of α-Al is dendritic structure with long primary arms for all three alloys. The (Al)+(Mg_2Si) eutectic has a lamellar morphology, where long Mg_2Si plates alternate with α-Al. Primary Mg_2Si crystals have a regular polyhedral shape and are situated in the centers of eutectic colonies. Addition of Li showed modification effect on eutectic lamellas transforming them from plates to fibers, which was observed on deep etched specimens. The addition of (Ti + Zr) produces slight grain refinement effect. The length of dendrite arms in alloy T is smaller in comparison with H and L alloys.



a) b) c)

Fig. 1 Microstructure of H (a), L (b), T (c) alloys in as-cast state

The composition of the phases was measured by EDS analysis using SEM. The α-Al solid solution of L and T alloys contain Mg (**Table 2**) and Mn. The Mg content in solid solution measured in SEM using 15 kV acceleration voltage is 2.44 wt.%. The small Si content measured in case of SEM EDS analysis obviously originated from surrounding Mg_2Si lamellas or from those lying beneath the surface. The Mg distribution across the dendrite arm is not homogeneous and varies in the range from 2.2 to 2.5 wt.% for L alloy, between 2.5 to 2.6 for T alloy.

Table 2 Average composition of α-Al solid solution in L and T alloys measured by SEM EDS (wt.%)

Alloy	Al	Mg	Si	Mn	Ti	Zr
H	96.63	2.57	0.34	0.46	-	-
L	96.56	2.60	0.39	0.45	-	-
T	96.53	2.28	0.32	0.47	0.21	0.20

The morphology of primary Mn-containing phase observed in both L and T alloys is shown in **Fig. 1**. Its chemical composition is: Al - 74.45 at.%, Mn - 15.78 at.%, Si - 4.73 at.%, Fe - 0.04 at.%, and this phase can be identified as α-Al(Mn,Fe)Si, what is often observed in commercial aluminum casting alloys after Mn alloying.

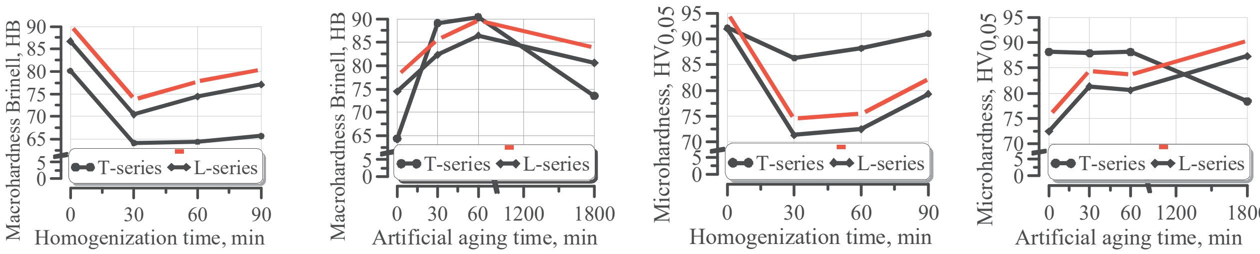
2.2 Mechanical tests

The results of hardness measurements are summarized in **Fig. 2**. One can expect that hardness of tested alloys should initially grow and than gradually decreases due to growth of β-precipitates and loss of their coherency with aluminum matrix. This is the most general tendency observed for all age hardenable aluminum alloys typically for Al-Mg-Si or Al-Si-Mg alloys.

Solution treatment even for 30 min results in significant decreasing of both HB and $HV_{0.05}$ values. Longer soaking lead to further hardness decreasing. Observed hardness decreasing is the result of two processes, which simultaneously occurs during heating. The first one is the eutectic spheroidization. The higher solution treatment temperature leads to faster eutectic lamella decomposition into smaller segments and spheroidizing effect. The second process is the dissolution of β″ precipitates formed during natural aging.

After 30 min of artificial aging, increasing of HB and HV0.05 were detected for all alloys studied. After 90 min aging, hardness and microhardness reached maximum for L and T alloys. Prolonged aging up to 1800 min showed slight decreasing of HB for L and T alloys. Same hardness changes were observed during HV0.05 measurements.

EDX analysis of α-Al showed reduction of Mg during solution treatment. In the as-cast condition α-Al contained 2.3 wt.% Mg. After heating during 30 minutes content Mg in α-Al decreased up to 1.6 wt.%. Increasing duration of heating to 90 minutes or more, leads to gradual increase of Mg content in α-Al up to 1.8 wt.%.



a) b) c) d)

Fig. 2 Changes of Brinell hardness (a, b) and microhardness (c, d) of L, T alloys

One of the most accessible and informative methods is tensile test. In spite of it wide spread, the standard method is rather expensive and raw material exhaustive, which is rather unsuitable during obtaining and researching new alloy with limitation of the cast. The automated ball indentation (ABI) test is proved to be easy in usage and it is a powerful tool in determination of mechanical properties of materials.

There are several methods of indentation for the determination of mechanical properties in a nondestructive ways which are based on the measurement of force applied to the tested sample and on the depth of indenter penetration [8-10]. The indentation cycle, which includes loading and unloading process, causes elastic, elasto-plastic and plastic deformations of tested material and it is usually represented in the form of relation „force - indentation depth“. Based on this indentation diagram, it is possible to calculate elastic modulus of the material among other mechanical properties.

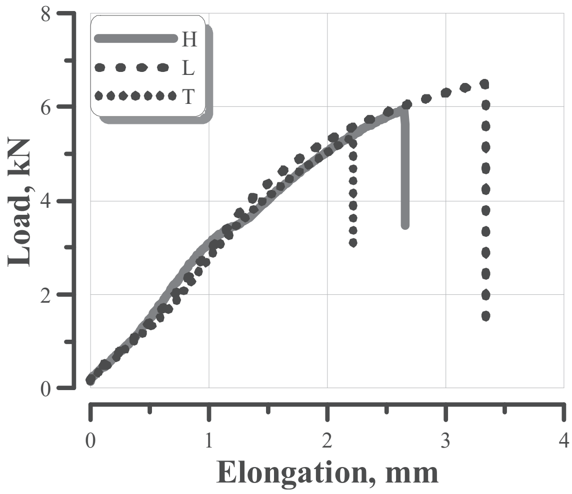
Tensile tests were carried out with the automated ball indentation on H, L and T samples. Obtained results by ABI method and standard method are shown in **Table 3**. Typical stress-strain curve and ABI curve are represented in **Fig. 3**. Elastic modulus for aluminum alloys, according to the standard, can vary in range from 70 GPa to 80 GPa. Due to it, obtained results satisfy the required range. Further application of ABI method for the research alloys can bring accurate results. Yield strength, obtained from ABI tests, was calculated by the formula (1):

$$R_{p0.2} = 2.5\ HB \qquad (1)$$

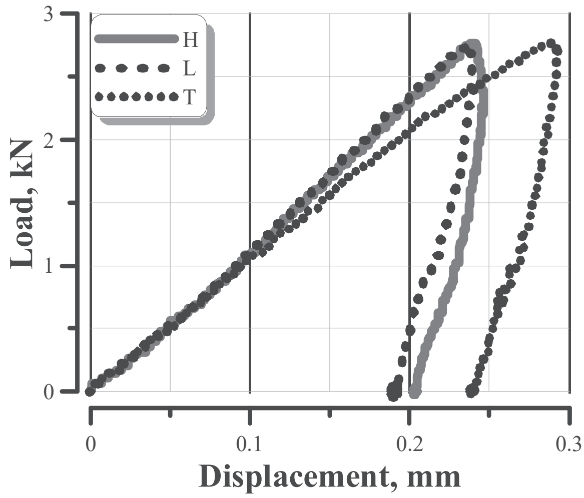
The calculations of the yield strength were discussed in the work [11]. The value of the coefficient (2.5) was chosen empirically.

Table 3 Results of the tensile tests provided by standard and ABI methods

Alloy	HB, ABI	HB, Classic method	E, (GPa) ABI	$R_{p0,2}$, (MPa) Tensile test	$R_{p0,2}$, (MPa) ABI
H	86	76	79	117	180
L	91	87	77	163	182
T	73	80	74	138	151



a)



b)

Fig. 3 Tensile curves of standard tensile test (a) and ABI (b)

CONCLUSIONS

1. In as-cast state the microstructure of Al-Mg-Si-Mn alloy consists of three phase: α-Al solid solution grains, (Al) + (Mg_2Si) eutectic and Mg_2Si primary crystals. α-Al exhibits dendrites morphology with well developed arms. Eutectic has plate-shaped morphology of lamellas and Mg_2Si primary crystals.
2. Both alloys of AlMg5Si2Mn + Li and AlMg5Si2Mn + (Ti + Zr) showed the similar results of macro- and microhardness tests. Mechanical tests prove that solution treatment reduces the hardness of investigated alloys due to the disintegration of the Mg_2Si lamellas, decreases the content of alloying elements in solid solution.
3. Artificial aging leads to increase of the alloy hardness. Optimal values of macro- and microhardness was achieved after 30-60 minutes of aging time. Overaging of evaluated alloys was monitored after the 60 minutes of artificial aging indicated by extremely decrease of hardness..
4. Automated ball indentation test shows that this method allows rapid orientation in mechanical properties of tested materials. Obtained values using ABI method may effectively facilitate modification of parameters of heat treatment and content of alloying elements. Yield stress calculated using equation $R_{p0.2} = 2.5\ HB$ has the same trend as tensile values. More accurate correlations between values of yield stress, which were obtained by tensile tests and ABI, require more data for statistic. Calculation given in this paper shows that this trend is quite promising.

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