VARIABILITY OF MECHANICAL AND CORROSION PROPERTIES OF STANDARDIZED ALUMINUM-BASED ALLOYS

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Abstract

Aluminum alloys show a high strength-to-weight ratio and a relatively good corrosion resistance making them prospective structural materials in many fields. In material standards of commercial Al alloys, chemical composition is always defined as concentration ranges of alloying elements and impurities. In some cases, concentration ranges allowed within one material grade are relatively wide. It can be expected that mechanical and corrosion properties of one material grade are also variable that can be problematic in some applications. Three commercial aluminum casting alloys (AlSi5Cu4Zn, AlSi9Cu3Fe, AlSi10MgMn) with chemical composition on the lowest and highest content of alloying elements prescribed by their material standards were studied. Microstructure, selected mechanical properties (hardness, tensile testing) and corrosion resistance (short-term exposure AUDI test) were determined. The properties of the alloys were tested in as-cast state and after their recommended heat treatment. The significant influence of chemical composition on the properties of aluminum alloys was found.

Keywords: Aluminum alloys, mechanical properties, material standards, heat treatment, corrosion test

1. INTRODUCTION

Material standards of commercial alloys are basic documents for casting producers as well as for their customers. Keeping the prescribed chemical composition of alloys should be the basis for achieving their constant and reproducible properties. Material standards, however, in many cases tolerate contents of alloying elements or impurities within a relatively wide range, which can lead to very significant differences in mechanical properties of alloys. In the past, the range of alloying elements in the alloy was justified by analytical methods at that time, which did not allow us to obtain immediately the results of the melt composition during its preparation. At present, spectral methods allow the melt composition to obtain in the order of several tens of seconds, allowing the manufacturer practically immediately to adjust the chemical composition of the alloy as needed [1]. At present, therefore, there is no longer a rational reason to tolerate such a wide range of alloying elements in alloys if we neglect the tendency of some alloy producers to keep the contents of more expensive alloying elements at their minimum values in order to save money. For illustration, the minimal and maximal contents of alloying elements and the differences of these values for selected frequently used aluminum alloys are in the **Table 1**. It shows that for some alloys the difference between the minimum and maximum alloying elements contents is about 3%, while in others it is almost 10%. It is clear that these differences must necessarily influence the microstructure and properties of these alloys. Differences in alloy properties may increase after heat treatment. In the case of these alloys, the highest tolerances are for silicon, copper and magnesium. In the case of silicon, its influence on the mechanical properties of the alloy in the as-cast state or after its heat treatment is not significant, even though the silicon particles have a high tendency to coarsening during long-term annealing. The situation in the case of copper and a combination of magnesium with silicon is different. Copper is a basic element for increasing the mechanical properties of aluminum alloys. It efficiently reinforces the α-Al solid solution already in as-cast state similarly with Mg and Zn.

Table 1 Minimum and maximum contents of alloying elements according to material standards in selected aluminum alloys [1]

Alloy - Czech material standard	Alloy - alternative material standard	Composition (wt. %)	Minimal content of alloying elements (MIN) (wt. %)	Maximal content of alloying elements (MAX) (wt. %)	MAX - MIN difference (wt. %)
ČSN 42 4357	DIN 1725	Al Si5 Cu4 Zn	7.0	16.2	9.2
ČSN 42 4384	EN AC 46400	Al Si9 Cu1 Mg	8.8	17.1	8.3
ČSN 42 4339	DIN 226, EN AB46000	Al Si9 Cu3 Fe	10.2	18	7.8
ČSN 42 4352	DIN 1725	Al Si11 Cu2	11.7	18.4	6.7
ČSN 42 4353	EN 1706-98	Al Si6 Cu2	7.5	13.9	6.4
ČSN 42 4356	AC 47000	Al Si12 Cu	11.8	16.6	4.8
ČSN 42 4361	A 02130	Al Cu8 Fe Si	8.4	12.5	4.1
ČSN 42 4332	AC 42000	Al Si7 Mg	6.2	9.9	3.7
ČSN 42 4315	A 02420	Al Cu4 Ni2 Mg2	6.8	10.1	3.3
ČSN 42 4331	A 359, EN AC-42100	Al Si10 Mg Mn	9.3	12.5	3.2

Copper is a key element enabling precipitation hardening in aluminum alloys. Different copper contents in the alloy will also result in a significant change in the corrosion resistance of the alloy. The effect of the combination of magnesium and silicon is also very important in precipitation hardening. The other alloying elements or impurities (Fe, Mn, Ni) form an intermediate phase disturbing the homogeneity of the microstructure, thereby reducing the plasticity of the alloy. Morphology changes in some intermediate phases after heat treatment were occurred. These microstructure changes can improve the mechanical properties of the alloys [2-5].

The aim of this work was to find out how the chemical composition of the alloy within its material standard affects its microstructure and other selected properties.

2. EXPERIMENT

The differences between the behavior of 3 selected commercial, often used aluminum alloys with chemical composition in the lowest and the highest level of alloying elements specified in their material standards are documented in this work. Altogether, 6 different alloys were tested. The alloys ČSN 42 4331 [6], ČSN 42 4339 [7], ČSN 42 4357 [8] were studied. The ČSN 42 4339 alloy is used in die casting technology, the other alloys are used for the production of castings for general use.

The alloys were prepared by melting the components in an electric induction furnace in a protective Ar atmosphere. The melt was poured into a massive brass mold. The average rate of cooling at crystallization was approximately 10 Ks^{-1}. The castings were then processed by machining and samples were taken to observe their microstructure, measure the Brinell hardness with a 2.5 mm diameter WC ball at a load of 62.5 kg. Uniaxial tensile tests with the samples of 10 mm in diameter were also performed. The chemical composition of prepared alloys is in **Table 2**. The MS in the table indicates the material standard of the alloy. L and H are alloys with the minimal or maximal content of alloying elements. The properties of alloys have been studied both in the as-cast state and after their recommended heat treatment specified in the relevant material standard. All studied alloys were treated by precipitation hardening except the alloy ČSN 42 4339. This alloy is only used in the condition after casting under pressure. Therefore, heat treatment of this alloy has not been realized in this work. The recommended heat treatment modes of studied alloys are in **Table 3**.

Table 2 Chemical composition of prepared alloys (wt.%), MS denotes the composition of the alloy according to its material standard, L and H denotes an alloy with a chemical composition at the lower or upper limit of the material standard

	Sample	Cu	Ni	Mg	Fe	Si	Ti	Zn	Mn	Sn
ČSN 42 4331	**31 MS**	max. 0.1	-	0.2-0.45	max. 0.8	9-10.5	max. 0.15	max. 0.1	0.1-0.4	-
	31-L	0.01	-	0.18	0.08	8.91	0.01	0.01	0.07	-
	31-H	0.13	-	0.49	0.74	10.61	0.16	0.01	0.34	-
ČSN 42 4339	**39 MS**	2-3.5	-	0.1-0.5	max. 1	8-11	max. 0.15	max. 1.2	0.1-0.5	max. 0.1
	39-L	1.91	-	0.12	0.03	8.11	0.02	0.01	0.11	0.02
	39-H	3.41	-	0.51	1.01	10.82	0.16	1.22	0.44	0.07
ČSN 42 4357	**57 MS**	3-5	max. 0.3	max. 0.5	max. 1.2	3-6	-	1-2.5	max. 0.6	max. 0.1
	57-L	2.92	0.01	0.01	0.10	2.81	-	1.12	0.01	0.03
	57-H	4.87	0.26	0.53	1.25	6.11	-	2.61	0.58	0.07

Table 3 Heat treatment modes of studied alloys [1]

Alloy	**Heat treatment**	
	Homogenization	Artificial ageing
31-L, 31-H	530°C / 6 h, ↓ H_2O (50°C)	180°C / 8 h, air
57-L, 57-H	505°C / 8 h, ↓ H_2O (80°C)	155°C / 4 h, air

The microstructure of the prepared alloys was observed by the light microscope Olympus PME 3, the chemical composition of the alloys was determined using the optical emission spectrometer GD Profiler 2, the uniaxial tensile and pressure tests were performed using the LaborTech 5005 universal testing machine and the Brinell hardness measurement on the Heckert WPM hardness machine. The corrosion resistance of the studied alloys was evaluated using a simple AUDI exposure test. Cylindrical samples of alloys were exposed to the test solution (aqueous solution containing 2.3 wt.% HCl and 1.8 wt.% NaCl) for 2 hours. After the exposure, mass and dimensional changes were determined and the corrosion rate was calculated. The depth of penetration of the corrosive medium into the sample surface also was determined.

3. RESULTS AND DISCUSSION

Microstructure of alloys

The microstructure of all studied alloys observed by the light microscope is in the **Figures 1-3**. The microstructure of alloys containing alloying elements in the lowest and the highest level of their material standards does not differ significantly in a number of alloys. In the case of alloys with a significant difference in the iron content at the lowest and the highest limits of their material standard, the dimensional plates of the β-AlFeSi phase noticeably disturbing the structural homogeneity of the alloy were observed. Significant differences in microstructures at the as-cast state and after recommended heat treatment were shown. A common feature is the coarsening of the silicon particles, and some alloys also show signs of the initial stage of fragmentation of the intermediate phases containing iron.

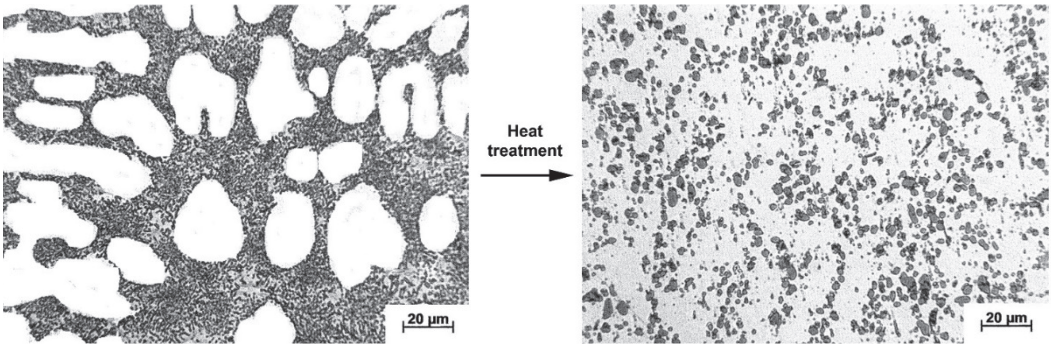

Figure 1a Microstructure of 31-L alloy - as-cast (left) and after heat treatment (right)

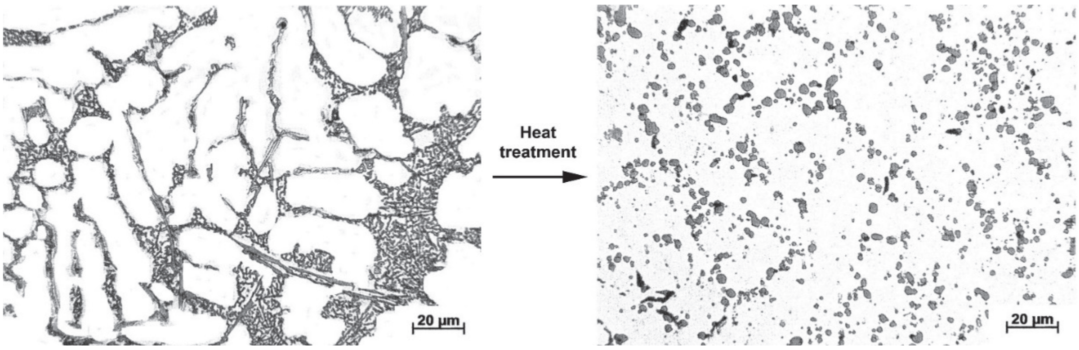

Figure 1b Microstructure of 31-H alloy - as-cast (left) and after heat treatment (right)

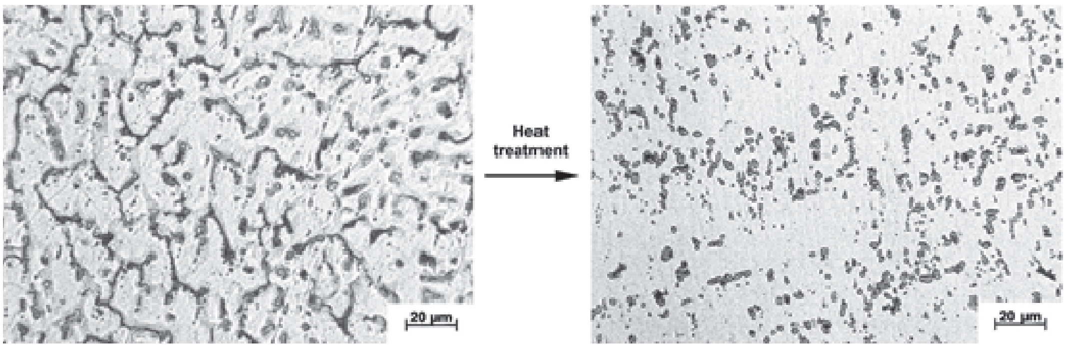

Figure 2a Microstructure of 57-L alloy - as-cast (left) and after heat treatment (right)

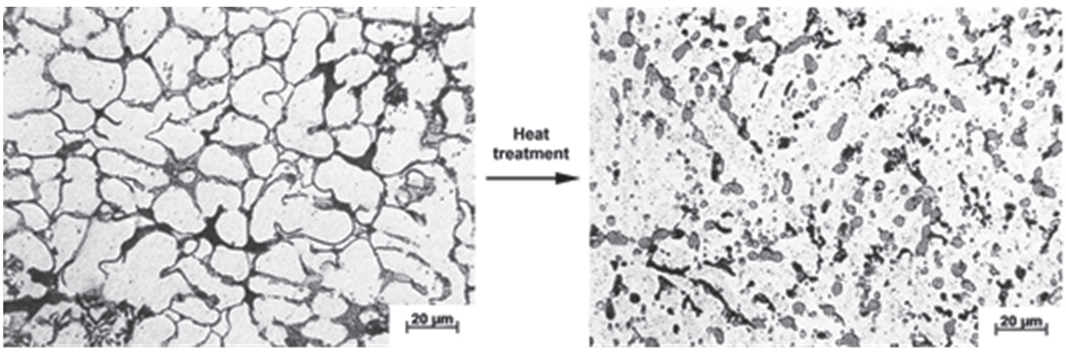

Figure 2b Microstructure of 57-H alloy - as-cast (left) and after heat treatment (right)

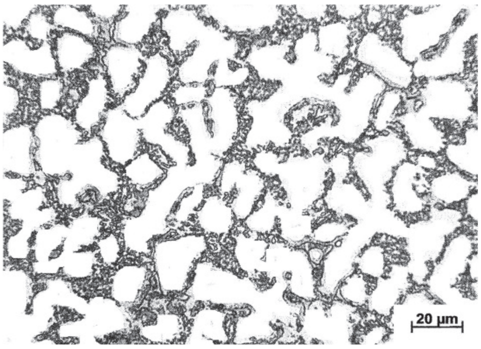

Figure 3a Microstructure of 39-L alloy (as-cast)

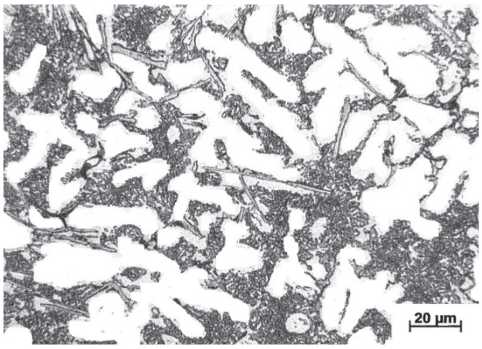

Figure 3b Microstructure of 39-H alloy (as-cast)

Mechanical properties

Mechanical properties of studied alloys are in the **Table 4**.

Table 4 Mechanical properties of alloys (behind the slash there is the standard deviation σ_{n-1}). L and H denotes an alloy with a chemical composition at the lower or upper limit of the material standard. HT indicates the alloy after its recommended heat treatment. YS and UTS denotes the yield strength or strength limit of the alloy.

Alloy	AlSi10MgMn - 31				AlSi9Cu3Fe - 39		AlSi5Cu4Zn - 57			
	L	L (HT)	H	H (HT)	L	H	L	L (HT)	H	H (HT)
HB	63/3	99/7	85/1	132/9	67/4	105/2	58/1	58/5	108/2	115/6
YS (MPa)	78/4	145/8	84/7	189/15	82/8	160/11	92/8	149/12	148/12	249/11
UTS (MPa)	152/12	204/11	159/9	249/9	169/9	229/8	152/12	209/4	179/11	312/8

Hardness

Brinell hardness (measured with 2.5 mm diameter WC ball at a load of 62.5 kg) of studied alloys is in the **Table 4**. No increase in hardness after heat treatment of alloy 57-L due to the low amount of precipitation hardening elements was observed. For alloys containing alloying elements at the upper limit of their material standard, precipitate hardening lead to increase in Brinell hardness. The best result was found in the 31-H alloy, the increase in hardness after precipitation hardening was about 55%.

Tensile testing

The character of the tensile diagrams of studied alloys did not differ significantly. For all alloys, relatively low plasticity is typical, due to a significant amount of the intermediate phases in the microstructure, which significantly disturbs structural homogeneity and the mechanical load significantly affect the effects of the intermediate phases as stress concentrators. The results of the uniaxial tensile test on cylindrical bars are in **Table 5**, which shows the yield strength and ultimate tensile strength values. As expected, the largest differences were found in alloys containing copper (39 and 57), where the yield strength and ultimate tensile strength values at the lower or upper limit of their material standard varied almost twice.

Corrosion test

The results of the corrosion test are shown in **Table 5**, where the calculated corrosion rate and corrosion depth of penetration into the surface sample (DPS) are shown. In the case of alloys 39 and 57, by differences of one order of magnitude in the corrosion rate of the alloys with the composition at the upper limit of the alloying elements content as compared to the alloys at the lower limit of the alloying elements content were found.

Table 5 Corrosion properties of studied alloys, behind the slash is the standard deviation $\sigma_{n-1.}$ L and H denotes an alloy with a chemical composition at the lower or upper limit of the material standard. HT indicates the alloy after its recommended heat treatment. DPS indicates the depth of penetration of corrosion environment into the surface of the material.

Alloy	AlSi10MgMn - 31				AlSi9Cu3Fe - 39		AlSi5Cu4Zn - 57			
	L	L (HT)	H	H (HT)	L	H	L	L (HT)	H	H (HT)
Corrosion rate ($mm \cdot a^{-1}$)	0.18 / 0.04	0.45 / 0.02	0.61 / 0.03	0.65 / 0.11	0.06 / 0.01	0.64 / 0.05	0.11 / 0.01	0.15 / 0.01	0.83 / 0.01	2.05 / 0.09
DPS (µm)	70 / 30	157 / 16	131 / 34	172 / 23	25 / 18	167 / 32	56 / 19	52 / 13	225 / 18	207 / 36

4. CONCLUSION

The results of the experiments showed significant differences in the microstructure and mechanical properties of the studied aluminum alloys with the minimum and maximum content of alloy elements within their material standards. The initial assumption that the highest differences in microstructure and properties are reflected in alloys with wide permissible ranges of alloying elements (ČSN 42 4357, ČSN 42 4339) has been confirmed. Differences in properties of alloys increase further after their recommended heat treatment. In the case of alloys ČSN 424339 and ČSN 42 4357, differences of one order of magnitude in the corrosion rate of the alloys with the composition at the upper limit of the alloying elements content as compared to the alloys at the lower limit of the alloying elements content were found. It can be assumed that differences in the chemical composition of alloys within their material standard will result, for example, in change of their casting and other physical properties. Extreme cases of chemical composition of alloys (to the minimum or maximum content of alloy elements) have been studied in this work. Fortunately, in real conditions, the occurrence of alloys with the chemical composition that were studied in this work is unlikely to occur. Nevertheless, in isolated cases, the situation may occur and this may explain the inadequate properties of the alloy.

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