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INFLUENCE OF THE CHEMICAL COMPOSITION ON THE DUCTILITY OF AN AlSiCuZnFe RECYCLING FOUNDRY ALLOY

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Abstract

The secondary foundry alloy of the type AlSiCuZnFe is one of the most common materials for several applications, mainly in the automotive industry. The main alloy within the AlSiCuZnFe family is the foundry alloy A226 (AlSi9Cu3(Fe)), which is a recycling alloy. The relatively low ductility of A_f < 3 % is not sufficient for various applications leading to a limited applicability of the A226. This study focuses on the investigation of the systematic compositional variations within and outside of the alloy's tolerance band and illustrates the achievable values for the elongation to fracture. It can be shown, that yield strength of permanent mold cast samples ranges from 80 MPa to 200 MPa, while elongation varies between 1 % and > 12 % in the as-cast state, just by varying the alloying elements. This microstructure-property relationship is interpreted in the light of thermodynamic calculations and metallographic investigations.

Introduction

Generally, in most cases secondary foundry alloys have wide ranges for alloying elements. In consideration of this fact, the range for various applications for those alloys is very large. In particular the secondary foundry alloy A226 (permanent mold casting variant AlSi8Cu3, high pressure die casting variant AlSi9Cu3) is characterized by an attractive combination of good fluidity and acceptable mechanical properties. Therefore the alloy is mostly used for casting parts like different types of cases, engine parts or oil pans, but not for parts where high ductility is needed. Due to the current efforts in energy consumption reduction and minimizing the CO_2 emissions during the component manufacturing and usage, secondary foundry alloys will remain to be a preferred material for casting parts. For this reason many investigations on the mechanical properties according to the effectiveness of alloying elements within the tolerance band were done [1-9]. From previous studies [1-6, 9] the performance of the alloy A226 is well known. In most of the cases the elongation to fracture is < 4 % and thus too low for casting parts which need high ductility. Therefore the aim of this study was to quantify the mechanical properties within and outside of the tolerance band of alloying elements according to the standard of A226 (for American standard A226 is comparable to A380). On basis of permanent mould casting and high pressure die casting experiments selective properties of the alloy were generated with special focus on the ductility behaviour by varying the alloying elements.

Experimental procedure

The evolution of the mechanical properties was done by the use of industry-relevant permanent mould and high die pressure casting experiments. For the investigation within the alloying band (Table 1) of the A226, a systematic variation of the main elements, such as silicon, copper, magnesium, manganese, zinc and iron, was done. The definition of the chemical composition limits was based on the alloy standards EN AB-46000 (EN AB-AlSi9Cu3(Fe)) for HPDC and EN AB-46200 (EN AB-AlSi8Cu3). Based on these results, the increase of the ductility was done by varying the elements iron, manganese, magnesium and copper within and outside of the tolerance band of A226, which is also shown in Table I. The design of the alloy for the casting experiments was based on a systematic and permutative combination of the element contents. This was done by the adding binary Al-X master alloys (X = Si, Mg, Mn, Fe) and pure Cu and Zn.

Table I. Chemical composition limits of the experimental trials and standard specification of the A226 (in weight-%)

Element	Experimental limits according to the standard	Experimental limits for increasing the ducility	Standard	
			EN AC 46000	EN AC 46200
Si	8.0 – 11.0	7.5 – 9.0	8.0 – 11.0	7.5 – 9.5
Cu	2.0 – 3.5	0.5 – 2.0	2.0 – 4.0	2,0 – 3.5
Mg	0.1 – 0.5	0.05 – 0,3	0.05 – 0.55	
Mn	0.15 – 0.55	0,1 – 0,3	≤ 0.55	0.15 – 0.65
Fe	0.4 – 1.2	0,4 – 0,6	≤ 1.3	≤ 0.8
Zn	0.3 – 1.2	0,4 – 0,7	≤ 1.2	

In this study two different casting methods were used for the evaluation of the different solidification rates. For a solidification rate about 3 K/min a steel mould was used and preheated to a temperature of 320 ± 5 °C. The mould was coated by using boron nitride prior each casting. Those tensile specimens (Figure 1) were prepared according to standard DIN 60125:2004-01 (gauge length 48 mm, diameter 8 mm). For the investigation on higher solidification rate (about 20 K/min), high pressure die casting tensile specimens were used (Figure 2). The cast plates have a thickness of about 3 and 4 mm. The tensile specimens were taken from the position of 4 mm thickness and were prepared according to standard ÖNorm EN ISO 6892-1. The evaluated mechanical properties reflect average values of at least three separately cast rods.

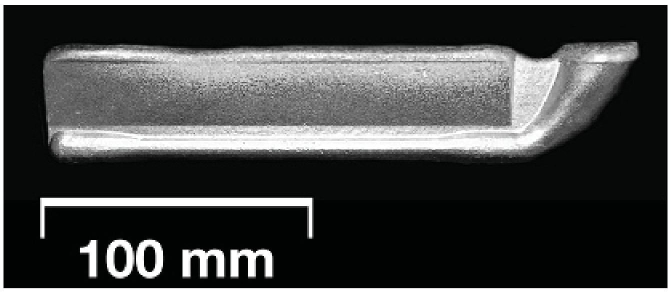

Figure 1. Tension specimens for permanent mould casting

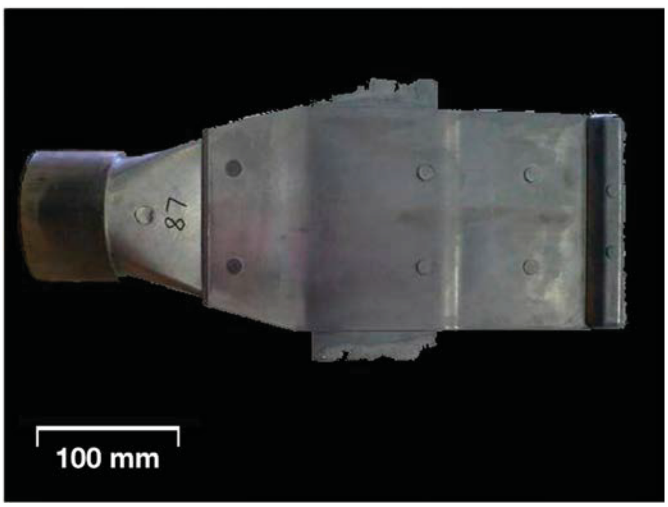

Figure 2. Tension specimens for high pressure die casting

Results and Discussion

In general the secondary foundry alloy A226 (AlSi9Cu3(Fe)) for HPDC and EN AB-46200 and AlSi8Cu3 for permanent mould casting) shows a wide spread in the mechanical properties. In this study the A226 achieved a maximum value for ductility with permanent mould casting specimens of about 4 % in the as-cast state and without modification of the eutectic-silicon. For this ductility level the strength is very low at about 100 MPa. Figure 3 to 6 shows the influence of the Fe, Mn, Cu and Fe content on the yield strength and on the elongation to fracture for a typical composition of the A226 in as-cast state. For the development of these diagrams 48 different alloys within the tolerance band of A226 were prepared. Under used conditions in this study, the plots are showing that the increase of Fe, Mg and Cu content, decreases the ductility dramatically.

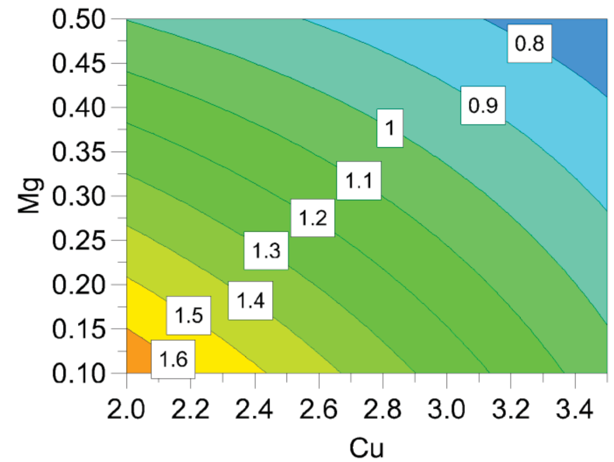

Figure 3. Influence of the chemical composition on the fracture elongation in [%]; Composition: 9.5% Si, 2.75% Cu, 0.3% Mg

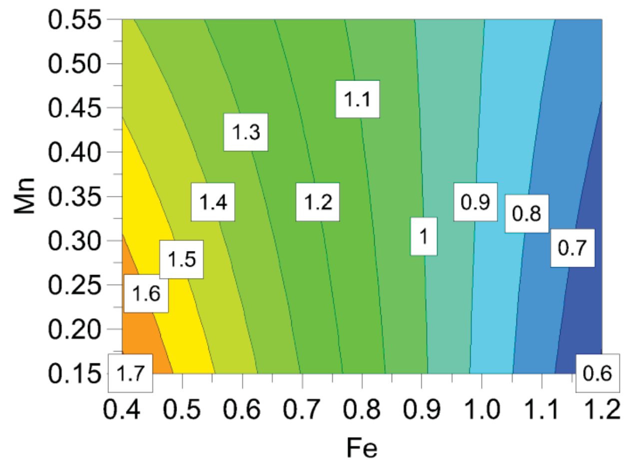

Figure 4. Influence of the chemical composition on the fracture elongation in [%]; Composition: Mg; 9.5% Si, 0.35% Mn, 0.8% Fe

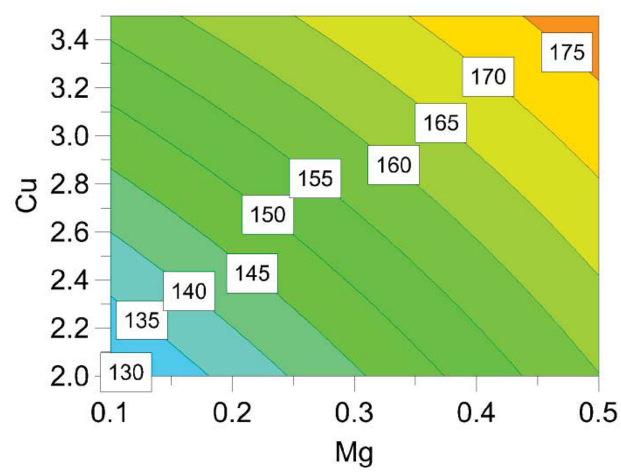

Figure 5. Influence of the chemical composition on the yield strength in [MPa] depending on Cu and Mg contend; Composition: 9.5% Si, 2.75% Cu, 0.3% Mg

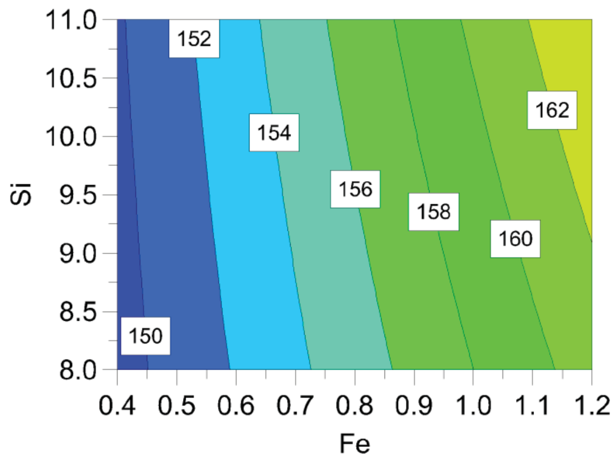

Figure 6. Influence of the chemical composition on the yield strength in [MPa] depending on Si and Fe contend; Composition: 9.5% Si, 0.35% Mn, 0.8% Fe

The decrease of the elongation to fracture with an increase of alloying elements (with the exception of Mn improving ductility at higher Fe-contents) can be explained by a fracture triggering effect of brittle phases with a high aspect ratio. It could be shown in many previous publications [3, 7, 8, 10, 11] that the decrease of the ductility is affected on the increase of the iron content. The morphology of the iron intermetallic phases plays a major role for the ductility of AlSi-Alloys. Especially the plate shaped β–Al_5FeSi–phase with its high aspect ratio triggers crack formation because of its stress concentration effect [13]. The high stress concentration results from dislocation pile-ups at the particle-matrix interface, which lead to micro-cracks at the Fe-containing IMPs [15]. As a further mechanism causing cracks the decohesion of the matrix from the IMPs is postulated [16], which leads to the β phase acting like a two-dimensional inner notch. Hence, it is obvious that an increase of the volume fraction of the IMPs has an immediate effect on the fracture strain. The addition of Mn, has two adverse effects: An increased Mn content stimulates the formation of the α-$Al_{15}(Fe,Mn)_3Si_2$ phase, which due to its polyhedral morphology is regarded as less prone to microcracking. Also adding Mn increases the total content of intermetallic phases thus can also decrease the ductility. With low Fe content, i.e. with a low fraction of β-phase, the unmodified Si-plates can trigger cracks. Furthermore it shows that Cu and Mg decrease the ductility. A large amount of Mg and Cu is dissolved in the primary and eutectic α-Aluminum, mostly due to the distinctive grain segregation and partly due to high super saturation. Their contribution to the strength increase in the as-cast state comes mainly from the solid solution hardening and the formation of GP zones (natural aging). Therefore the strength and ductility level of the alloys is depending on the quantity and morphology of Fe-containing IMP, the eutectic silicon, and the hardening characteristics by Mg and Cu as well as the formation of intermetallic phases of Q-$Al_5Cu_2Mg_8Si_6$ and Θ-Al_2Cu–phase [3,7,8]. The standard of the A226 doesn't use a modification of the eutectic silicon by strontium, but this can increase the ductility significantly. By using the lower tolerance limit of the alloying elements the elongation to fracture raises nearly 7 % (under used continues in this study) in the as-caste state. Without modification of the eutectic silicon, the increase of solidification rates also increases the ductility (High pressure die casting). For higher values of the elongation fracture the decrease of hardening elements like Mg and Cu seems to be necessary. For this reason the investigation of decreasing the Cu-content, below the tolerance limit of the A226 was done. Table II shows three variants within and four variants outside the tolerance limit of A226 (variants in permanent mould casting (PMC) and high die pressure casting (HDPC)). The table illustrates that the reduction of the copper content increases the ductility significanlyt. Variant 4 which represents average chemical composition of A226, offers only an elongation to fracture from about 1.2 % (for PMC). The reduction of Cu combined with the modification of the eutectic-silicon (e.g. Variants 1 to 3) shows the increase in ductility up to over 15 % (Variant 1). The level of yield strength decreases simultaneous to nearly 80 MPa.

As mentioned before the decrease of the elongation to fracture with an increase of alloying elements is contributed to brittle intermetallic phases. At higher Fe levels (Variants 4 and 5), the ductility decreases of the major amount of β–Al_5FeSi phase. At lower Fe-content the amount of intermetallic phases Q-$Al_5Cu_2Mg_8Si_6$ and Θ-Al_2Cu plays a major rule on the ductility level of the alloy.

Table II. Chemical composition limits of the experimental and standard specification of the A226 (in weight-%); Dispersion of IMP calculated with Pandat[17] in disequilibrium; Cu-content outside of the tolerance band of A226 are only masked with -, --, and ---. What means Cu under 2 %, much lower 2 % and much more lower than 2%.

No.	Chemical Analysis						Θ-Al_2Cu	β-Al_5FeSi	α-$Al_{15}(FeMn)_3Si_2$	Q-$Al_5Cu_2Mg_8Si_6$	A_f [%]	R_p [MPa]	Casting method
	Si	Cu	Mn	Mg	Fe	Zn							
1*	8	--	0.15	0.1	0.4	0.3	0.6774	0.8905	0.6865	0.145	15.7	80.8	PMC
2*	8	-	0.15	0.1	0.4	0.3	1.1084	0.8919	0.6921	0.1525	8.9	104.6	PMC
3*	8	2	0.15	0.1	0.4	0.3	1.5668	0.8934	0.6976	0.1525	4.9	125.8	PMC
4	9	2.5	0.35	0.3	0.8	0.3	1.9984	1.5812	1.8434	0.5438	1.2	162.8	PMC
5	11	3.5	0.55	0.5	1.2	0.3	2.975	2.2606	3.0311	1.0036	0.4	182.7	PMC
6*	8	---	0.15	0.1	0.4	0.5	0.5088	0.8897	0.6864	0.1436	11.7	91.4	HPDC
7*	8.5	--	0.25	0.1	0.6	0.8	0.8578	1.1284	1.2479	0.0635	3.5	125.3	HPDC

*Sr-modified, PMC stands for permanent mould casting; HPDC stands for high pressure die casting

In consideration of the amount of the intermetallic phases at variants 3 and 1, only the decrease of Θ-Al_2Cu can be observed. From the viewpoint of analysis micrographs which are shown in Figure 7 – 9 (variants 1, 4 and 5), the decrease of Θ-Al_2Cu is clearly recognized. Thus it can be assumed that in variants 4, 5 and 7 the indication of crack formation is depending at the Fe-containing IMPs. With lower Fe-content like in variants 1, 2, 3 and 6, i.e. with a low fraction of β-phase, the unmodified Si-plates can trigger cracks. At modified eutectic silicon the fraction of Θ-phase plays the major rule on the ductility and hardness level in Al-Si-alloys. But not only a high ductility level is important, rather the right combination between elongation to fracture (tensile strength) and yield strength. Hence to get optimized properties the right adjustment of the hardening elements Cu and Mg is necessary. The decrease of the elongation to facture by increasing the solidification rate plays an important rule within the tolerance band of the A226. There is no modification of the eutectic silicon required, which has a significant effect on ductility. Faster solidification rate increases the ductility because of a finer microstructure. This is particularly the case, for iron rich phases and the eutectic-silicon.

Comparing variants 1 and 6 in Table II, which have nearly the same chemical composition, the permanent mould casting variant shows a higher ductility level compare to the high pressure die casting variant.

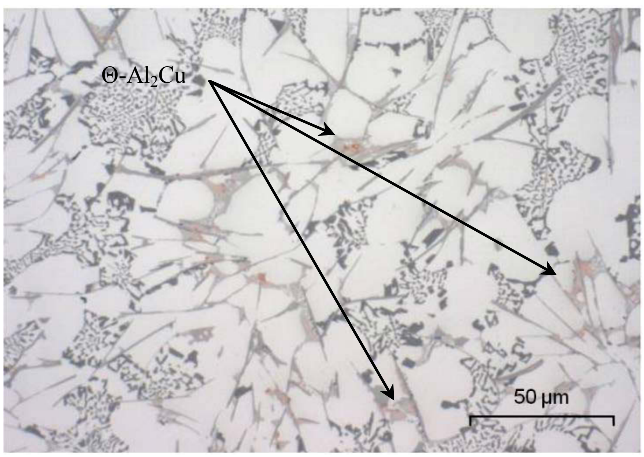

Figure 7. Micrograph X 500 for variant 5

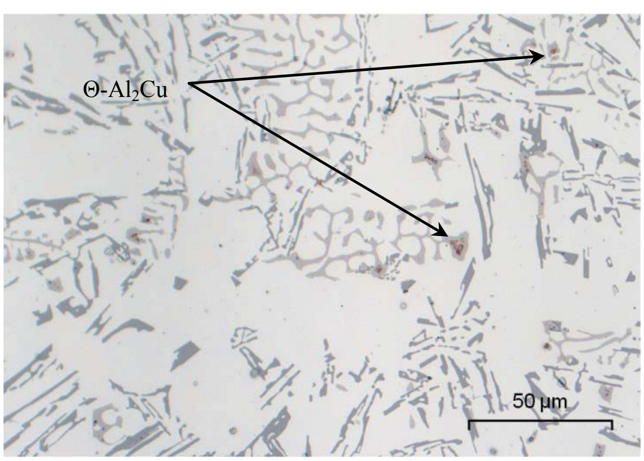

Figure 8. Micrograph X 500 for variant 4

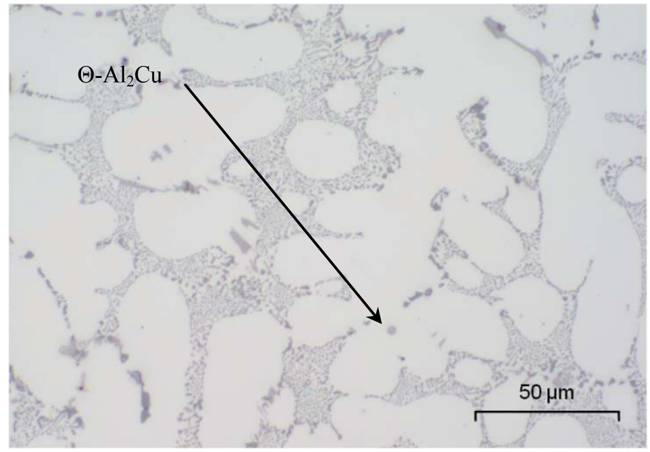

Figure 9. Micrograph X 500 for variant 1

That may be explained by the higher amount of biflims at high pressure die casting as in the permanent mould casting variants [18]. It has been shown, that the secondary foundry alloy A226 has a large spread in the chemical composition and therefore associated with a wide spared of mechanical properties. By leaving the tolerance limit, especially the decrease of Cu, the ductility increases. But in general secondary foundry alloys are always affected with higher amount of Cu (> 0.5 %), which is contributed to their production process due the recycling route. This fact leads to the problem that such secondary foundry alloys cannot be used for security relevant parts at the moment. Not only because of the ductility and strength level are too low, furthermore the high Cu-content leads to increased corrosion. Here an investigation of the influence of copper on above mentioned properties has to be conducted.

Conclusions

The standard tolerance band for all alloying elements of the secondary casting alloy A226 (permanent mold casting variant AlSi8Cu3, HDPC variant AlSi9Cu3) opens up a broad scope for selective adjustments of alloys to meet specific requirements. For evaluating the influence of the main alloying elements, 48 different alloy compositions according to a systematic test schedule were cast at AMAG test foundry. For this case the yield strength varies between 110 MPa and 200 MPa and elongation to fracture between 0.35 and nearly 4.0 % in the as cast. In order to study the increase of the ductility, variants outside of the tolerance band of A226, different variants were cast at LKR test foundry (Leichmetallkompetenzzentrum Ranshofen GmbH, Ranshofen). For this propose the effect of decreasing the Cu-content, modification of the eutectic-silicon and the effect of increasing the solidification rate was investigated.

The decrease of the Cu-content leads to significant increase of the elongation to fracture. Variants in permanent mould casting and with strontium modification are showing values above 15 % for A_f. Simultaneously the strength level decreases to nearly 80 MPa. But with a determined combination of hardening elements and strontium modification, an elongation to fracture with nearly 10 % and yield strength from about 120 MPa in as-cast state (permanent mould casting) is achievable. With heat treatment (which is not part of this study) the mechanical properties increases, especially the yield strength. Thus, it is possible to increase the ductility significantly by outgoing of the tolerance limit of A226.

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References

[1] H. Kaufmann, W. Fragner and P. J. Uggowitzer: Influence of variations in alloy composition on castability and process stability. Part 1: Gravity an pressure casting processes, Int. J. Cast. Metals Res. 18, (2005), S. 273-278.

[2] H. Kaufmann, P. J. Uggowitzer: Metallurgy and processing of high-integrity light metal pressure castings, ISBN-13:978-3-7949-0754-0, Schiele & Schön, (2007) S. 215-251.

[3] P. Pucher, H. Antrekowitsch H. Böttcher, H. Kaufmann, P.J. Uggowitzer: Influence of ompositional variations on microstructural evolution, mechanical properties and fluidity of the secondary foundry alloy AlSi9Cu3. International Journal of Cast Metals Research 23 (2010), S. 375 – 383.

[4] R. Smith, C. H. Caceres, D. St.John: The microstructure os Al-Si-Cu-Mg alloys, Materials Research 96, Brisbane (1996) 140-143.

[5] M. Panušková, E. Tillová, M. Chalupová: Relation between mechanical properties and microstructure of cast aluminium alloy AlSi9Cu3, Strength of Materials 2008, Vol. 40, No. 1, 98 – 101.

[6] M. Zeren: Effect of copper and silicon contend on mechanical properties in Al-Cu-Si-Mg alloys, J. Mat. Proc. Tech. 169, 2005, 292 ─ 298.

[7] M. Zeren, Effect of copper annd silicon content on mechanical properties in Al-Cu-Si-Mg alloys: J. Mat. Proc. Techn. 169 (2005) 292-298.

[8] L. Wang, M. Makhlouf and D. Apelian: Aluminium die casting alloys – alloy composition, microstructure, and properties-performance relationships, Int. Metals Reviews 40 (1996) 221-238.

[9] TMS Paper von 2011

[10] S. Onurlu, A. Tekin: Effect of heat treatment on the insoluble intermetallic phases present in an AA6063 alloy, J. Mat. Sci. 29 (1994) 1652-1655.

[11] H. Tanihata, T. Sugawara, K. Matsuda, S. Ikeno: Effect of casting and homogenizing treatment conditions on the formation of Al–Fe–Si intermetallic compounds in 6063 Al–Mg–Si alloys, J. Mat. Sci. 34 (1999) 1205-1210.

[12] S. G. Shabestari: The effect of iron and manganese on the formation of intermetallic compounds in aluminium–silicon alloys, Mat. Sci. Eng. A 383, (2004), S. 289-298.

[13] L. Wang, M. Makhlouf and D. Apelian: Alloy selection for die castings using the quality Index, AFS Trans. 107, (1999), S. 231-238.

[14] C. M. Dinnis, J. A. Taylor, A. K. Dahle: As-cast morphology of iron-intermetallics in Al–Si foundry alloys, Scripta Mater. 53, (2005), S. 955-958.

[15] J. Lakner, W. Sillinger: Effect of iron on ageing of AlSi8Cu3 alloys, Key Eng. Mater. 44–45 (1990) S. 365-371.

[16] O. Vorren, J. E. Evensen, T. B. Pedersen: Microstructure and mechanical properties of AlSi (Mg) casting alloy, AFS Trans. 92,(1984), S. 459-466.

[17] http://www.computherm.com/pandat.html

[18] J. Campbell: Castings, ISBN 0 7506 4790 6, Butterworth-Heinemann, (2003).