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Effect of Addition of Ti on Selected Properties of AlSi5Cu2Mg Alloy

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Abstract

The paper focuses on the investigation of the influence of Ti on selected properties of the hypoeutectic aluminium alloy AlSi5Cu2Mg. AlSi5Cu2Mg alloy finds application in the field of production of high-strength cylinder head castings intended for the automotive industry due to the optimal combination of mechanical, physical and foundry properties. In commercial production, the maximum Ti content is limited by the manufacturer (Ti max. = 0.03 wt.%), which significantly limits the possibilities of refinement the alloy with Ti-based grain refiners. Therefore, the possibility of increasing the Ti content beyond the manufacturer's recommendation is considered in this work. The main aim of the work is to evaluate the influence of graded Ti addition (0.1; 0.2; 0.3 wt.% Ti) on the resulting mechanical and physical properties of the AlSi5Cu2Mg alloy. Simultaneously, the influence of increased Ti content on the microstructure of AlSi5Cu2Mg alloy is evaluated. The alloying element was introduced into the melt in the form of AlTi5B1 master alloy. The effect of T6 heat treatment on the resulting mechanical and physical properties and microstructure of the hypoeutectic AlSi5Cu2Mg alloy with graded Ti addition was also investigated in the experimental work.

Keywords: AlSi5Cu2Mg, Heat treatment, Mechanical properties, Titanium

1. Introduction

Hypoeutectic AlSi5Cu2Mg alloys have good specific strength, corrosion resistance, a favorable combination of mechanical and physical properties, and good casting properties [1]. In the automotive industry, they are used in the production of highly stressed components, such as cylinder heads. The AlSi5Cu2Mg alloy was designed by the manufacturer with a specific chemical composition. From the point of view of chemical composition, AlSi5Cu2Mg alloy is characterized by low Si content, close to alloys intended for metal forming processes [1]. Conventionally used alloys for highly stressed cylinder head castings (AlSi8Cu3 and AlSi7MgCu0.5) contain Si in the range of 6 to 10 wt.%. [2] The AlSi5Cu2Mg alloy is significantly limited by the Ti content (max. 0.03 wt.%). For optimal refinement of hypoeutectic alloys based on Al-Si, it is necessary to add 0.10 wt.% of Ti [3]. The chemical composition regulation set by the manufacturer therefore limits the use of standard refining elements based on Al-Ti-B. It is assumed that the strict chemical composition limiting the content of Ti in the hypoeutectic aluminium alloy AlSi5Cu2Mg is set to eliminate its negative effect on the thermal and electrical conductivity [4]. Choi in his studies reports a significant decrease in the thermal conductivity of the AlSiMg0.4Cu alloy due to the addition of 0.1 wt.% of Ti [4]. Thermal conductivity is an important material characteristic that significantly affects the functionality and service life of castings [5].

Titanium is used for the refinement of hypoeutectic Al-Si alloys. As is well known, refining of aluminium alloys is a process of using suitable elements (or their alloys) to refine the structure by increasing the number of crystallization nuclei for the α-(Al) phase [6,7]. By refining the structure of aluminium alloys, increased mechanical and casting properties, reduced porosity and susceptibility to tearing occur [3,8]. Ti is introduced into the melt in the form of master alloys based on Al-Ti and Al-Ti-B [3]. The refining effect of Ti alone in the form of master alloys based on Al-Ti is insufficient. $TiAl_3$ crystalline nuclei have a relatively high solubility in aluminium, which reduces the refining effect [3]. A better refining effect of hypoeutectic Al-Si alloys is achieved by the combination of Ti and B. The principle of refining Al-Si alloys with Al-Ti-B master alloy consists in the formation of crystallization intermetallic phases based on AlB_2, TiB_2 or $(Al,Ti)B_2$. [6,7]

The research is focused on evaluating the influence of graded Ti addition (0.1, 0.2, and 0.3 wt.% of Ti) and T6 heat treatment on the mechanical properties, physical properties and microstructure of the hypoeutectic aluminium alloy AlSi5Cu2Mg. In the experimental work, the addition of Ti was deliberately chosen to exceed the Ti content (Ti max. = 0.03 wt.%) set by the manufacturer. The main objective of the work was to find out to what extent the excess amount of Ti affects the resulting properties of the AlSi5Cu2Mg aluminum alloy.

2. Material and Methods

The hypoeutectic alloy AlSi5Cu2Mg was selected for the experimental work. The AlSi5Cu2Mg alloy without Ti addition was designated as the reference alloy (ref. alloy). The chemical composition of AlSi5Cu2Mg alloy is shown in Table 1. The specific chemical composition of the alloy (max. 0.03 wt.% of Ti) is determined by the manufacturer. As shown in Table 1, the AlSi5Cu2Mg alloy was pre-modified with Sr by the manufacturer as well.

Table 1.
Chemical composition of reference alloy [wt.%]

Si	Cu	Mg	Sr
5.55	1.98	0.35	0.008
Ti	**Cr**	**Mn/Fe**	**Al**
0.03	0.02	0.09	Bal.

The experimental alloys were obtained by refining the reference alloy with graded additions of Ti (0.1, 0.2 and 0.3 wt.%). Depending on the addition of Ti, the experimental alloys were designated Ti-0.1, Ti-0.2 and Ti-0.3. The chemical composition of the experimental alloys Ti-0.1, Ti-0.2 and Ti-0.3 is shown in Table 2, it can be seen that the actual Ti content was lower due to its incomplete dissolution.

The hypoeutectic alloy AlSi5Cu2Mg was melted in an electric resistance furnace and Ti was added to the melt at a temperature of 770 °C ± 5 °C. Ti was added in the form of AlTi5B1 master alloy. The experimental alloys were produced by gravity casting and melt was poured into a metal mold with graphite coating (Fig. 1). The temperature of the mold was maintained in the range from 160 °C to 180 °C. The casting temperature was 750 °C ± 5 °C due to the higher Ti addition and low solubility of the AlTi5B1 master alloy.

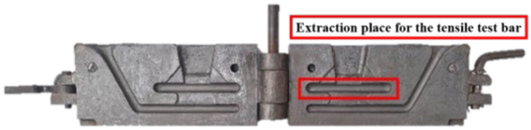


Fig. 1. Metal mold

Ten samples were produced for each experimental variant. Five experimental samples were evaluated in the cast condition and five samples were evaluated after heat treatment. Precipitation hardening heat treatment T6 was selected for the experimental work. The T6 thermal mode consisted of solution annealing at 500 °C ± 5 °C/6.5 hours, rapid cooling in water at a temperature of 80 °C ± 5 °C, and precipitation hardening at 250 °C ± 5 °C/4 hours. After heat treatment, the experimental samples were cooled in air.

The mechanical properties of the test samples were evaluated by a static tensile test according to EN ISO 6895-1. The static tensile test was performed with a universal tensile tester Inspekt desk 50 kN. A set of ten round bars with a diameter of 8 mm were made for each experimental variant. The tensile test bars (Fig. 2) were made by cutting and then turning from the casted samples. Half of the test bars were evaluated without heat treatment and half after T6 heat treatment.

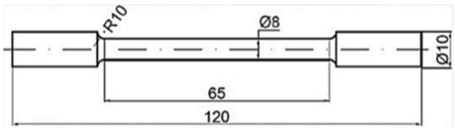


Fig. 2. Scheme of tensile test bar

The hardness of the experimental alloys was determined by the Brinell hardness test. The hardness of the experimental alloys was measured with a Brinell Innovatest Nexus 3000 hardness tester according the STN EN ISO 6506-1. The Brinell hardness was measured according to HBW 5/250/10 (carbide ball with a diameter of 5 mm, which is indented with a constant force of 250 kp for a loading period 10 s). Five hardness measurements were performed on each sample.

Table 2.
Chemical composition of experimental alloys [wt.%]

	Si	Cu	Mg	Sr	Ti	Cr	Mn/Fe	Al.
Ti-0.1	5.81	1.84	0.27	0.007	0.09	0.015	0.085	Bal.
Ti-0.2	5.72	1.88	0.23	0.005	0.17	0.008	0.092	Bal.
Ti-0.3	5.68	1.84	0.22	0.006	0.25	0.009	0.089	Bal.

The method used to determine the thermal conductivity of the samples was based on the measurement of the electrical conductivity using a Sigma Check 2 conductometer with a contact probe. The measurement was performed on the experimental samples in the cast state and after T6 heat treatment. Three measurements were made on each sample at different locations. The electrical conductivity measurements were performed at a laboratory temperature in the range of 20 to 25 °C. The measured values of electrical conductivity (σ) were then used in the empirical relationship (1), which was used to calculate the thermal conductivity (λ) of the experimental alloys:

$$\lambda = 4{,}29 \cdot \sigma - 13{,}321 \ [W \cdot m^{-1} \cdot K^{-1}] \qquad (1)$$

The microstructure of the experimental alloys was evaluated using a Neophot 2 optical light microscope and a TESCAN LMU II line electron microscope with a Bruker EDX analyzer. The microstructural analysis was performed on the experimental samples that showed the best combination of mechanical properties.

3. Research Results and Discussions

3.1. Mechanical Properties

The obtained values of the mechanical properties for the experimental alloys with graded Ti addition were compared with the reference alloy AlSi5Cu2Mg. Mechanical properties represent the average values of 5 measurements. Mechanical properties of the experimental alloys in the cast state are shown in Figure 3.

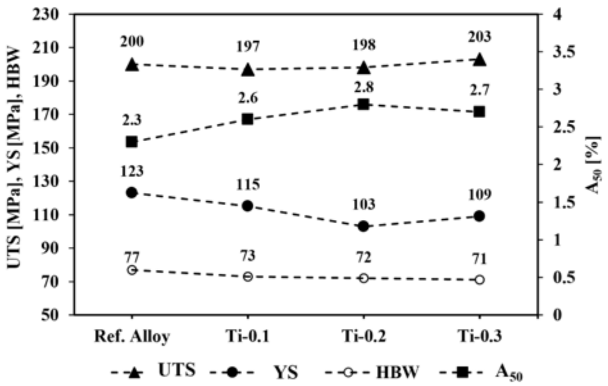


Fig. 3. Mechanical properties of experimental alloys as-cast state

The Ti-0.1, Ti-0.2 and Ti-0.3 alloys did not show a significant increase in UTS and HBW due to the effect of graded Ti addition, compared to the reference alloy AlSi5Cu2Mg. On the other hand, due to the effect of graded Ti addition, a decrease in YS was observed compared to the reference alloy. The YS of the experimental alloys Ti-0.1, Ti-0.2, and Ti-0.3 decreased on average by 6%, 17%, and 12%, respectively. The ductility of the experimental alloys increased with the addition of Ti. The experimental alloy Ti-0.2 showed the biggest increase in ductility with an average of 21% compared to the reference alloy. Conversely, the smallest increase of 13% was recorded for the Ti-0.1 alloy. An increase in ductility due to the Ti amount above the level of the reference alloy would represent a significant advance in ensuring flawless operation of highly stressed cylinder head castings. Increased ductility is crucial during thermal-mechanical loading of the cylinder heads from the point of view of preventing the occurrence of specific defects such as heat deformation and cracking, etc.

The mechanical properties of the experimental alloys after T6 heat treatment are shown in Figure 4. The UTS and HBW values of the experimental alloys with Ti addition were at the same level compared with the reference alloy. The YS of the Ti-0.1 alloy decreased by almost 6%, while the Ti-0.2 alloy showed an increase of 3% compared to the reference alloy. A significant increase in ductility was observed due to the effect of graded Ti addition. The highest ductility increase of 49 % was recorded for the Ti-0.1 alloy compared to the reference alloy. The ductility of the Ti-0.2 and Ti-0.3 alloys increased by 31% and 43%, respectively, compared to the reference alloy.

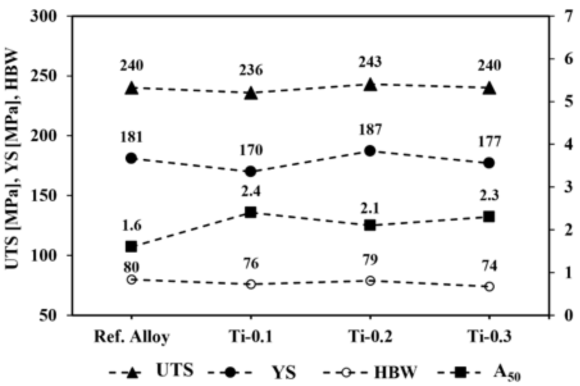


Fig. 4. Mechanical properties of experimental alloys after T6

The greatest benefit of Ti was a significant increase in the ductility of the experimental alloys in the cast and heat treated states. Refining of the AlSi5Cu2Mg alloys with a Ti addition above of recommended amount by the manufacturer resulted in an increase in ductility of more than 2%.

3.2. Physical Properties

In general, the thermal stability of Al-Si-Cu-Mg alloys is limited by the thermal stability of the strengthening precipitates Mg_2Si and Al_2Cu. Strengthening precipitates based on Mg and Cu are thermally stable up to about 200 °C. The subsequent increase in temperature leads to thickening and dissolution of the strengthening precipitates, resulting in a decrease in the mechanical properties of high-strength aluminum alloys based on Al-Si-Cu-Mg. Thermal stability is therefore a key design characteristic that determines the suitability of structural materials for specific applications. [5,9]

The physical properties of the experimental alloys are processed in Fig. 5. The electrical and thermal conductivity values are averages of 5 measurements. The electrical and thermal conductivity of Ti-0.1, Ti-0.2 and Ti-0.3 alloys decreased with increasing Ti addition compared to the reference alloy. The largest decrease in physical properties, 19%, was observed in the alloy with 0.3 wt.% of Ti addition. In general, any alloying element acts as a barrier to the free movement of electrons through the environment, resulting in a decrease in physical properties. In this case, intermetallic phases rich in Ti acted as barriers for the free movement of electrons through the environment. [10]

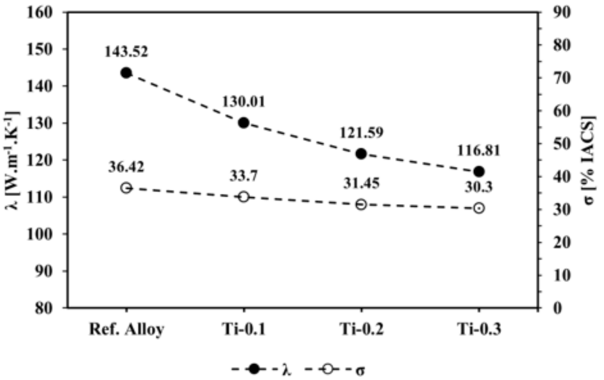


Fig. 5. Physical properties of experimental alloys as-cast state

Due to the effect of the T6 heat treatment, a positive increase in physical properties was observed (Fig. 6). The physical properties of the Ti-0.1 alloy decreased by an average of 12% compared to the AlSi5Cu2Mg reference alloy. The Ti-0.2 alloy showed a 1% increase in physical properties compared to the Ti-0.1 alloy. The lowest physical properties were obtained with the alloy containing 0.3 wt.% of Ti. The Ti-0.3 alloy showed an average decrease in physical properties of 13% compared to the reference alloy.

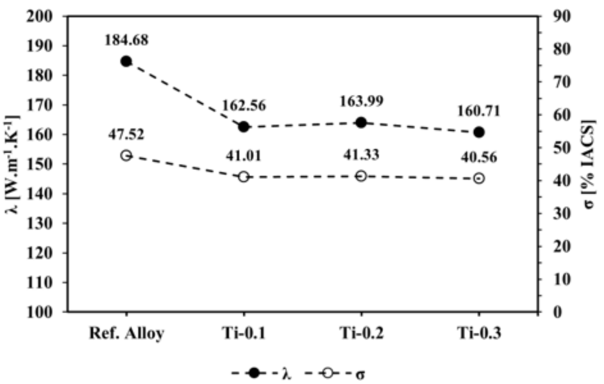


Fig. 6. Physical properties of experimental alloys after T6

A literature review showed that the presence of Ti in Al-Si-Cu-Mg alloys leads to a decrease in physical properties [4]. A negative decrease in physical properties has already been demonstrated in the presence of 0.1 wt.% of Ti. The chemical composition determined by the manufacturer, which limits the Ti content to 0.03 wt.%, was therefore probably implemented to eliminate the negative effect of the presence of Ti on the physical properties of aluminium alloys intended for high-stress automotive applications.

3.3. Microstructural evaluation and EDX analysis

No significant microstructural changes were observed in the cast state as a function of Ti addition. The microstructure of the experimental alloys in the cast state consists of the primary phase α-(Al), modified eutectic Si and intermetallic phases based on Fe and Cu (Fig. 7). Due to the pre-modification of the AlSi5Cu2Mg alloy by the manufacturer, eutectic Si can be observed in the form of imperfectly rounded grains. Hard and brittle Fe-based intermetallic phases are excluded in the form of plate-like formations. In the cast state, Cu-based intermetallic phases were observed in two modifications. In the form of oval grains with a high concentration of Cu and in the form of the ternary eutectic Al-$CuAl_2$-Si. The presence of Cu-based intermetallic phases was also demonstrated by EDX analysis (Fig. 8). Near the Cu-rich phases, the presence of Fe was detected. SEM analysis showed the presence of small sharp-edged particles in Ti-0.3 alloy (Fig. 9). These particles were identified by EDX analysis as Ti-based particles. The presence of Ti-based particles indicates that there was no complete dissolution of the AlTi5B1 master alloy in the alloy with the addition of 0.3 wt.% Ti.

The microstructures of the experimental alloys after T6 heat treatment are shown in Fig. 10. The microstructure of the experimental alloys depends on the wt.% of Ti and does not change significantly. As a result of the T6 heat treatment, intermetallic phases Mg and Cu are dissolved into a homogeneous α-(Al) phase and their subsequent elimination in the form of Al_2Cu and Mg_2Si strengthening precipitates. The Al_2Cu and Mg_2Si strengthening precipitates increase the strength and hardness of the aluminum alloy. Spheroidization of eutectic Si occurs as a result of T6 heat treatment. Eutectic Si is excluded in the form of perfectly round grains. Fe-based intermetallic phases were not affected by T6 heat treatment. By EDX analysis, intermetallic phases were observed in the form of thick plate formations with a split ends (Fig. 11). Fe-based intermetallic phases were identified as Al_5FeSi-based phases.

Fractographic evaluation was performed on experimental alloys with Ti addition. The matrix of Al-Si-Cu-Mg alloys is formed by an α-(Al) phase metal matrix characterized by high plastic properties. Eutectic Si crystals and intermetallic phases are excluded in the α-phase matrix. Intermetallic phases are precipitated as hard and brittle cleavage facets with almost zero plastic properties.

In Fig. 12a-c it can be seen that the relief of the fracture surfaces of the experimental alloys in the cast state with graded Ti addition does not differ significantly. Eutectic Si can be observed in the form of small plates. The cleavage facets present on the fracture surfaces are due to the presence of larger silicon phases and intermetallic phases based on Cu and Fe. Cleavage facets are indicated by yellow arrows on the fracture surfaces.

The fracture surfaces of the experimental alloys Ti-0.1, Ti-0.2 and Ti-0.3 after T6 do not show significant changes depending on the wt.% of Ti (Fig. 12d-f). Heat treatment T6 leads to spheroidization of eutectic Si, which results in an improvement of

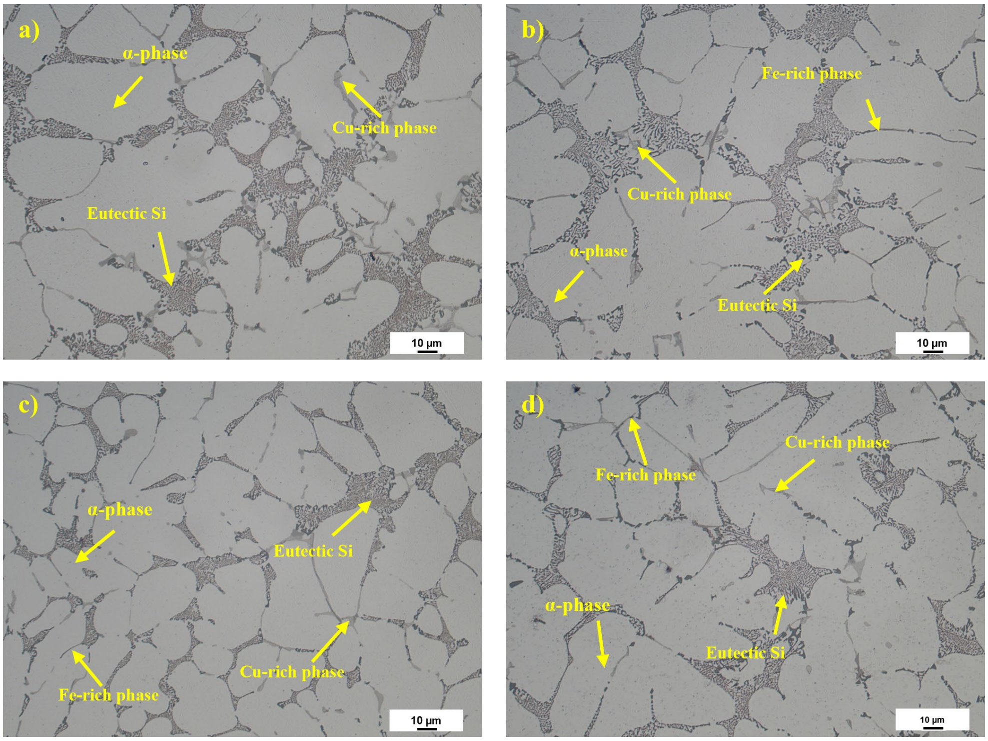
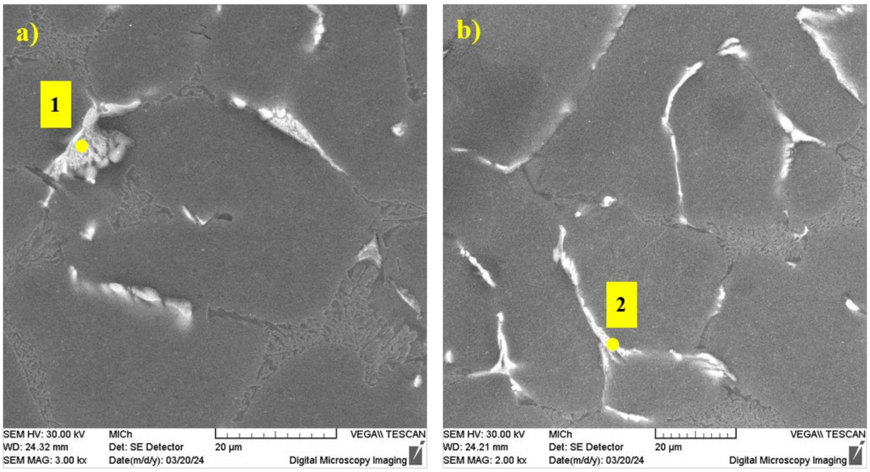


Fig. 7. Microstructural evaluation of experimental alloys in as-cast state: a) reference alloy AlSi5Cu2Mg, b) Ti-0.1, c) Ti-0.2, d) Ti-0.3



Spectrum: 1

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Mg	12	K-series	2.31	2.25	2.74	0.17
Al	13	K-series	76.63	74.77	81.93	3.87
Si	14	K-series	8.02	7.83	8.24	0.41
Fe	26	K-series	0.62	0.60	0.32	0.05
Cu	29	K-series	14.91	14.55	6.77	0.41
		Total:	102.49	100.00	100.00	

Spectrum: 2

El	AN	Series	unn. C [wt.%]	norm. C [wt.%]	Atom. C [at.%]	Error (1 Sigma) [wt.%]
Mg	12	K-series	2.60	2.29	3.02	0.20
Al	13	K-series	73.91	65.10	77.44	3.75
Si	14	K-series	5.10	4.50	5.14	0.29
Fe	26	K-series	3.28	2.89	1.66	0.13
Cu	29	K-series	28.64	25.23	12.74	0.77
		Total:	113.53	100.00	100.00	

Fig. 8. Morphology of Cu-rich intermetallic phases with corresponding EDX analysis spectrum (as-cast state, H_2SO_4 etch.): a) Ti-0.1, b) Ti-0.2

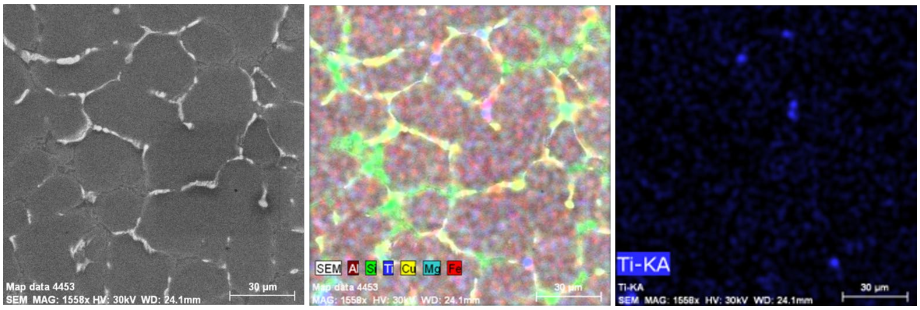


Fig. 9. Undissolved Ti particles with corresponding EDX mapping (Ti-0.3, as-cast state, H_2SO_4 etch.), SEM

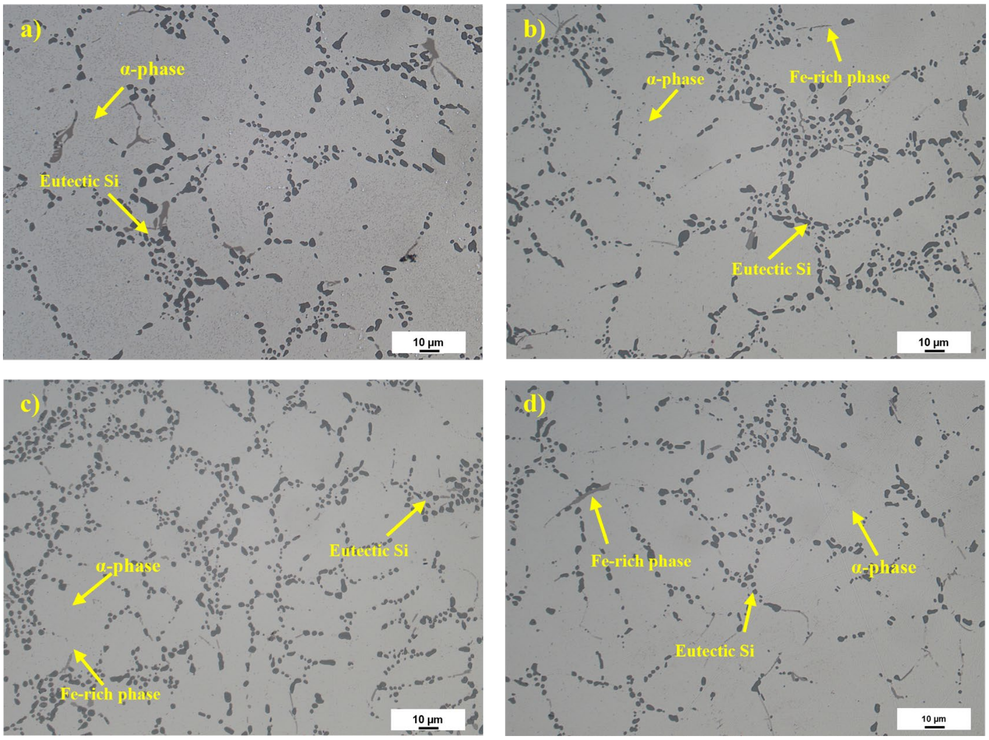


Fig. 10. Microstructural evaluation of experimental alloys after heat treatment T6: a) reference alloy AlSi5Cu2Mg, b) Ti-0.1, c) Ti-0.2, d) Ti-0.3, H_2SO_4 etch

Fig. 11. Fe-rich intermetallic phases with corresponding EDX mapping of chemical elements (Ti-0.3, T6, H_2SO_4 etch.), SEM

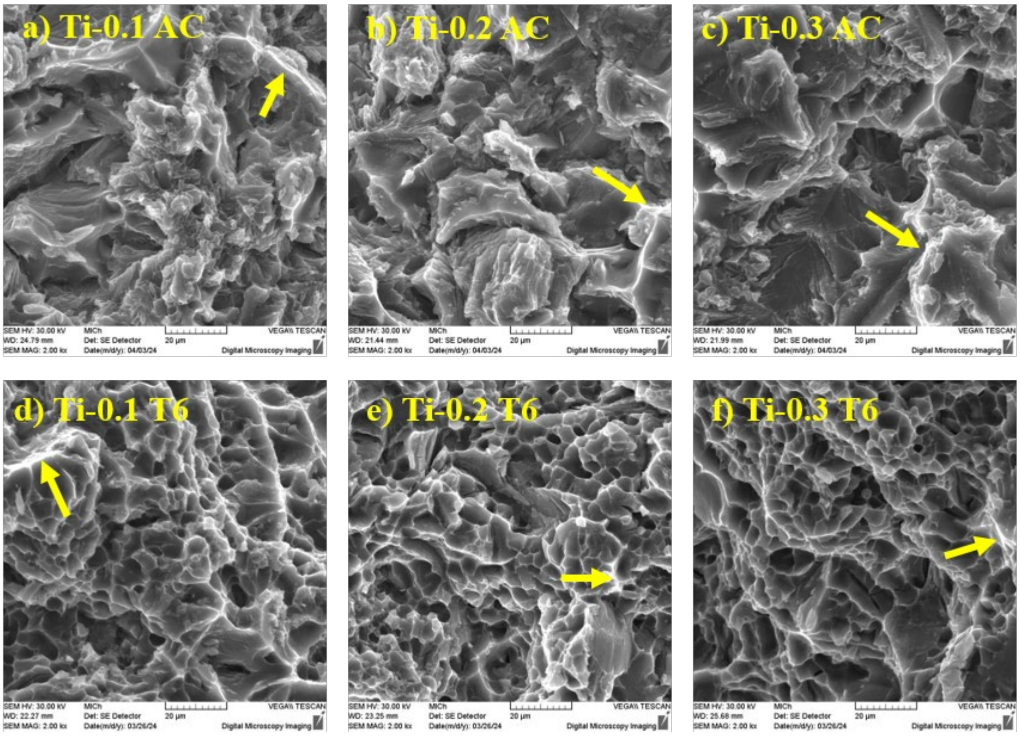


Fig. 12. Fractographic evaluation of experimental alloys with addition of Ti: a) Ti-0.1 AC, b) Ti-0.2 AC, c) Ti-0.3 AC, d) Ti-0.1 T6, e) Ti-0.2 T6, f) Ti-0.3 T6, SEM

the mechanical properties of Al-Si alloys. Spheroidized Si is observed on the fracture surface in the form of isolated particles. In the case of heat-treated Al-Si alloys, the mechanism of transcrystalline ductile failure with dimple morphology and plastically deformed ridges is also applied. The occurrence of intermetallic phases is manifested by the presence of cleavage facets.

4. Conclusions

The work focused on evaluating the effect of graded wt.% of Ti on the mechanical, physical, and microstructural properties of the hypoeutectic aluminium alloy AlSi5Cu2Mg. The addition of Ti was deliberately increased to exceed the manufacturer's chemical composition specification, which limits the Ti content to max. 0.03 wt.%. Based on the results obtained, it can be concluded that:

- No significant increase in UTS and HBW was observed in the alloys with Ti addition in the cast state and after T6 compared to the alloy without Ti addition.
- The YS of the experimental alloy with the addition of Ti in the cast state decreased slightly. No significant change in YS was recorded by T6 heat treatment of the experimental alloy Ti-0.1 – Ti-0.3.
- The addition of Ti had a positive effect on the ductility values both in the cast state and after T6 heat treatment. In the cast state, the biggest ductility increase of 21% was observed with the Ti-0.2 alloy. Due to the T6 effect, the Ti-0.1 alloy showed the best ductility values, with a 49% increase in ductility compared to the reference alloy.
- The addition of Ti resulted in a significant decrease in the physical properties both in the cast state and after the T6 heat treatment. The physical properties of the experimental alloys decreased with increasing wt.% of Ti.
- The microstructure of the experimental alloys consists of the primary phase α-(Al), modified eutectic Si and intermetallic phases based on Fe and Cu. Undissolved Ti particles were observed by the EDX analysis in alloy with addition of 0.3 wt.% Ti. Spheroidization of the eutectic Si occurs as a result of the heat treatment. The microstructure of the alloys is not significantly different depending on the wt.% of Ti.

Based on the obtained results, it is assumed that the chemical composition regulation limiting the Ti content in the AlSi5Cu2Mg alloy was chosen to suppress the negative influence of Ti on the physical properties of the AlSi5Cu2Mg alloy. However, it is necessary to consider the potential benefit of Ti addition in terms of achieving increased ductility, which is critical for cylinder head castings.

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References

[1] Bolibruchová, D., Sýkorová, M., Brůna, M., Matejka, M. & Širanec, L. (2023). Effect of Zr addition on selected properties and microstructure of aluminum alloy AlSi5Cu2Mg. *International Journal of Metalcasting*. 17(4), 2596-2611. DOI: 10.1007/s40962-023-01048-z.

[2] Javidani, M. & Larouche, D. (2014). Application of cast Al-Si alloys in internal combustion engine components. *International Materials Reviews.* 59(3), 132-158. DOI: 10.1179/1743280413Y.0000000027.

[3] Sigworth, G.K. & Kuhn, T.A. (2015). Grain refinement of aluminum casting alloys. *International Journal of Metalcasting.*1, 31-40. DOI:10.1007/BF03355416.

[4] Choi, S., Kim, Y., Kim, Y. & Kang, Ch. (2019). Effects of alloying elements on mechanical and thermal characteristics of Al-6wt-%Si-0.4wt-%Mg-(Cu) foundry alloy. *Materials Science and Technology*. 35(11), 1365-1371. DOI: 10.1080/02670836.2019.1625170.

[5] Czerwinski, F. (2020). Thermal stability of aluminum alloys. *Materials*. 13(15), 1-49. DOI: 10.3390/ma13153441.

[6] Pourkia, N., Emamy, M., Farhangi, H. & Ebrahimi, S.H. (2010). The effect of Ti and Zr elements and cooling rate on the microstructure and tensile properties of a new developed super high-strength aluminum alloy. *Materials Science and Engineering: A*. 527(20), 5318-5325. DOI: 10.1016/j.msea.2010.05.009.

[7] Kashyap, K.T. & Chandrashekar, T. (2001). Effects and mechanism of grain refinement in aluminium alloys. *Bulletin of Materials Science*. 24(4), 345-353. DOI: 10.1007/BF02708630.

[8] Brůna, M., Remišová, A. & Sládek, A. (2019). Effect of filter thickness on reoxidation and mechanical properties of aluminum alloy AlSi7Mg0.3. *Archives of Metallurgy and Materials.* 64(3), 1100-1106. DOI: 10.24425/amm.2019.129500.

[9] Beroual, S., Boumerzoug, Z., Paillard, P. & Borjon-Piron, Y. (2019). Effects of heat treatment and addition of small amounts of Cu and Mg on the microstructure and mechanical properties of Al-Si-Cu and Al-Si-Mg cast alloys. *Journal of Alloys and Compounds*. 784, 1026-1035. DOI: 10.1016/j.jallcom.2018.12.365.

[10] Li, K., Zhang, J., Chen, X., Yin, Y., He, Y., Zhou, Z. & Guan, R. (2020). Microstructure evolution of eutectic Si in Al-7Si binary alloy by heat treatment and its effect on enhancing thermal conductivity. *Journal of Materials Research and Technology*. 9(4), 8780-8786. DOI: 10.1016/j.jmrt.2020.06.021.