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Microstructural Modification of AlSi5Cu2Mg Alloy by Tungsten Addition and Heat Treatment

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Abstract

Al-Si-Cu-Mg-based alloys are key materials for applications in the automotive and aerospace industries, mainly due to their low density, excellent castability, and high specific strength. However, their mechanical properties are often negatively affected by the presence of brittle, acicular eutectic silicon particles and long intermetallic phases with a high iron content, which have a negative impact on the overall toughness and strength of the material. This study systematically focuses on evaluating the individual and combined effects of microalloying with varying amounts of tungsten and T7 heat treatment on the microstructure of the hypoeutectic AlSi5Cu2Mg alloy. The results obtained showed that the addition of tungsten significantly refines the microstructure of the alloy already in the cast state. There is a reduction in the coarse-grained morphology of the primary α-Al phase and a significant refinement of the eutectic silicon, which changes its original shape to a finer and more compact one. At higher tungsten concentrations, extensive clusters of fine grains were observed, indicating its effective role in the heterogeneous nucleation of the eutectic phase. Another key finding is its ability to suppress undesirable iron-rich intermetallic phases, particularly β−Al_5FeSi acicular structures, which are transformed into shorter and more compact shapes. The combination of tungsten and T7 heat treatment further enhanced the synergistic effect and accelerated the spheroidization of eutectic silicon, promoting the formation of an almost perfect spheroidal morphology. At the same time, a significant modification of the Fe-phase shape to a less critical morphology was achieved.

Keywords: Al-Si-Cu-Mg alloy, Tungsten, Modification, Heat treatment

1. Introduction

Al-Si-Cu-Mg-based aluminum alloys are the basic material for modern manufacturing industries, especially in the automotive industry, where emphasis is placed on low weight, excellent castability, and high specific strength [1]. Thanks to their optimal combination of mechanical, physical, and casting properties, these alloys have become the preferred choice to produce highly stressed components such as cylinder heads, engine blocks, and pistons [2]. The performance of Al-Si-Cu-Mg alloys is limited by the microstructure formed during solidification, which consists of coarse dendritic networks of α-Al, brittle eutectic silicon, and iron-rich intermetallic phases, especially β-Al_5FeSi. These structural components act as stress concentrators, accelerate fracture initiation, and reduce the toughness and ductility of the material. Therefore, it is crucial to refine and modify them. Traditionally, elements such as Ti and Sr are used, while tungsten has proven to be an effective refiner and strengthening element in other alloy systems [3,4].

In the context of aluminum alloys, tungsten has an extremely high melting point (3 422 °C) and very limited solubility in liquid aluminum, making it a promising microalloying element for microstructure modification [5]. Preliminary studies suggest that the addition of tungsten to Al-Si-based cast alloys leads to the formation of a fine microstructure and increases hardness and wear resistance [6]. The mechanism of this phenomenon is that tungsten disperses in the aluminum matrix and can form stable intermetallic phases, such as $Al_{12}W$, which serve as effective heterogeneous nucleation centers for primary α-Al dendrites, thereby contributing to grain refinement [7]. In addition, it has been found that the presence of tungsten leads to a dispersion hardening mechanism, which contributes to an overall increase in the strength and toughness of the alloy [6].

Zykova et al. state in their study that the addition of tungsten in a concentration of 0.1 wt. % causes a positive modification of the morphology of eutectic silicon. This addition leads to a change in the original coarse, needle-like structure of Si to the desired fine fibrous structure. The result of this change is a reduction in the average size of Si plates by 1.5 to 2 times the original size. The mechanism of this refinement is associated with a change in crystallization processes, whereby the addition of tungsten shifts the eutectic precipitation start temperature to higher temperature ranges, approximately by 9 °C. This effect is considered to be a consequence of the action of tungsten as a "heterogeneous nucleation substrate" that promotes the formation of eutectic phases [8].

Given these challenges and the existing lack of literature, this study systematically focuses on evaluating the individual and combined effects of tungsten microalloying and T7 heat treatment. The main objective is to quantitatively assess the influence of graded tungsten additions on dendrite arm spacing, morphological modification of eutectic silicon, and the characteristics of iron-rich intermetallic phases, with the aim of clarifying the synergistic relationship between these two methods of material modification.

2. Experimental methodology

A non-standardized hypereutectic AlSi5Cu2Mg alloy was selected as the experimental material, which is used for casting high-stress components due to its specific properties. The AlSi5Cu2Mg alloy in its original state (without additives) served as a reference material for comparing the results.

As part of the experiment, three variants of the AlSi5Cu2Mg alloy were prepared with defined additions of tungsten in concentrations of 0.05, 0.10, and 0.15 wt.%. Each batch weighed 8 kg. Melting was carried out in an electric resistance furnace with a T15 regulator with a capacity of 15 kg in a graphite crucible, which was treated with a protective coating at a stable temperature of 750 ± 5 °C.

To ensure homogeneous distribution, the tungsten additive was prepared in advance in the form of AlW5 pre-alloy, which was melted separately in an induction furnace with a graphite crucible. After it had completely melted, the liquid metal was added in precisely calculated doses to the molten alloy in a resistance furnace. A series of ten identical experimental castings for each variant was then cast from the alloy treated in this way using the gravity casting method into preheated moulds at a temperature of 150 ± 5 °C. Five castings from each series were heat treated using the T7 regime, which included:

- solution treatment (500 ± 5 °C / 6.5 h),
- cooling in water (85 ± 5 °C),
- artificial aging (250 ± 5 °C / 4 h) with final cooling in air.

The variants of experimental alloys were subsequently designated as Ref. -alloy AlSi5Cu2Mg without tungsten addition and as alloys 0.05 W; 0.10 W and 0.15 W – based on the weight % of tungsten content in the AlSi5Cu2Mg alloy. The chemical composition of the alloys used in the experimental work is shown in Table 1. The chemical composition of the experimental alloys with graduated tungsten additions was evaluated using a VANTA X-ray spectrometer. Samples for structural analysis were prepared according to standard metallographic procedures. After preparation of the metallographic sections, the samples were etched with a 0.5% hydrofluoric acid (HF) solution. The microstructure prepared in this way was then observed using a Keyence digital microscope and TESCAN VEGA LMU II scanning electron microscopy.

Table 1.
Chemical composition of the AlSi5Cu2Mg alloys [wt.%]

	Si	Fe	Cu	Mn	Mg	Cr	W
Ref.	6.77	0.23	2.54	0.015	0.15	0.004	-
0.05 W	6.58	0.22	2.38	0.014	0.16	0.007	0.020
0.10 W	6.31	0.22	2.36	0.013	0.22	0.006	0.044
0.15 W	6.41	0.23	2.37	0.012	0.18	0.006	0.075

As part of the microstructural evaluation, the effect of the graded addition of W on grain refinement was assessed metallographically based on the DAS index evaluation:

$$DAS = L/(n-1) \tag{1}$$

where L is the total length of the main dendritic axis and n is the number of secondary branches. DAS index measurements were performed on cast sections. Three independent samples were analyzed for each alloying variant, with five measurements performed on each sample. The resulting values were determined as the averages of these measurements.

3. Results

3.1. Structure evaluation

Primary α-Al phase

The observed microstructure consisted of a primary α-Al phase, eutectic components of the Al-Si system, and intermetallic phases containing Cu, Mg, and Fe elements. When observed in sections magnified 200×, eutectic silicon was identified as dark areas of irregular shape, often lining the boundaries of dendritic cells (Fig. 1a,b,c,d). In images with a digital color filter applied to highlight the distribution, size, and shape of the dendritic network, dendrites with a typical branched tree-like morphological arrangement, forming the basic skeleton of the microstructure, were clearly identified in all cases. With increasing addition of the monitored element, no significant differences in the character of the grains of the primary α-Al phase were observed in these images. The DAS index was used for the quantitative evaluation of the grain size of the primary α-Al phase, and the measured values are shown in Table 2. No change in the morphology and distribution of the primary α-Al phase was observed due to heat treatment (Fig. 1e,f,g,h).

Table 2.
DAS index values of experimental alloys [μm]

Alloy	Ref.	0.05 W	0.10 W	0.15 W
DAS index	33.45	32.61	27.52	24.32

Experimental results showed that an initial addition of 0.05 wt. % tungsten led to only a slight decrease in the DAS index, but a subsequent increase in concentration to 0.10 wt. % and 0.15 wt. % W, a significant decrease in this value was observed, confirming the effective refinement of the dendritic structure. This phenomenon is primarily controlled by the segregation of tungsten, which accumulates in the liquid phase in front of the growing interface during solidification. This creates concentration undercooling, which changes the local chemical environment and growth kinetics. Strong tungsten segregation slows down the transverse growth of secondary dendritic arms. At higher W concentrations, this refining effect is enhanced, limiting overall dendrite growth and contributing to smaller and more desirable secondary spacing.

Si eutectic

Analysis of metallographic sections from the perspective of eutectic Si demonstrates the influence of tungsten addition on its morphology and distribution. The Al-Si-Cu-Mg alloy, even in its reference state (Fig. 2a), is equipped with eutectic with a coarse, incompletely rounded morphology, which is the result of pre-modification that changes the growth of eutectic from acicular to fibrous or rounded. However, the gradual addition of tungsten leads to a significant refinement of the eutectic silicon, which is evident from the gradual reduction in the size of the individual grains, best illustrated by the transition from Fig. 2a to Fig. 2b (0.05 wt. % W). This refining effect is probably related to the presence of tungsten, which acts as an effective nucleus for heterogeneous nucleation of the eutectic phase. Due to its limited solubility in molten aluminum, tungsten forms stable intermetallic phases that serve as nucleation centers for the growth of eutectic cells and increase their overall density. Increased nucleation also results in a refinement of the primary dendritic network, and smaller inter-dendritic spaces physically limit the growth of eutectic silicon particles and contribute to their finer morphology. At higher tungsten concentrations, specifically 0.10 wt. % and 0.15 wt. % (Fig. 2c,d), the formation of extensive clusters of fine, rounded eutectic silicon grains is also observed. This phenomenon can be explained by the agglomeration of tungsten nucleation nuclei in the melt, on the surface of which the eutectic then preferentially grows, leading to local accumulation of refined particles.

After applying T7 heat treatment (HT), the microstructure of the AlSi5Cu2Mg alloy changes significantly towards a more stable, rounded morphology of eutectic silicon. While in the reference alloy without tungsten, eutectic silicon occurs in the form of rounded grains (Fig. 3a), the addition of tungsten significantly promotes and accelerates this process. In alloys containing 0.05 wt. % W (Fig. 3b) and 0.10 wt. % W (Fig. 3c), significant spheroidization is visible, with silicon particles more evenly distributed and having a compact, spherical shape. This effect is most pronounced at the highest addition of 0.15 wt. % W (Fig. 3d), where the microstructure is the finest overall and the eutectic silicon achieves an almost perfect spheroidal morphology. This pronounced rounding is an expected result of high-temperature solution treatment, during which the system minimizes its total surface energy. It is assumed that the finer initial structure of tungsten alloys in the cast state, with a smaller distance between silicon particles, significantly accelerates the diffusion and coagulation process, leading to more efficient spheroidization. These favorable morphological changes directly affect the mechanical properties of the material, as the transformation of irregular particles into fine, rounded grains reduces stress concentration and creates conditions for increasing the plasticity and toughness of the material.

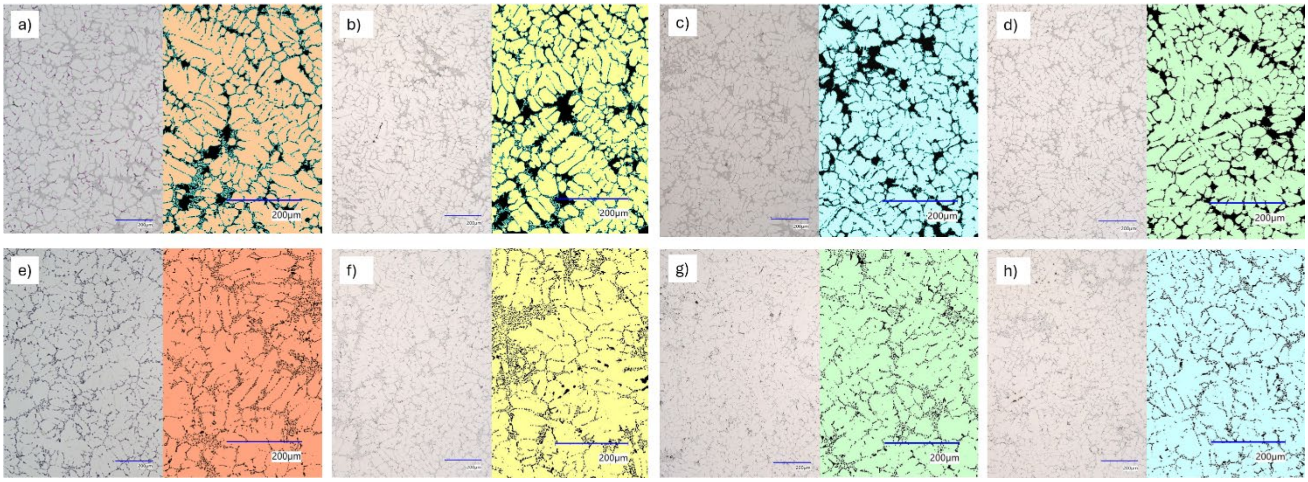

Fig. 1. Microstructure of the experimental AlSi5Cu2Mg alloy: a) Ref. alloy - cast state; b) 0.05 W alloy - cast state; c) 0.10 W alloy - cast state; d) 0.15 W alloy - cast state; e) Ref. alloy - HT; f) alloy 0.05 W - HT; g) alloy 0.10 W - HT; h) alloy 0.15W - HT

Intermetallic phases rich in iron

Analysis of the microstructure in the cast state revealed that the addition of tungsten has a significant effect on the morphology and distribution of iron-rich intermetallic phases, which are present in the reference alloy (Fig. 4a) mainly in the form of long, needle-like structures of the Al_5FeSi phase, known for its negative effect on mechanical properties. In addition to this needle-like morphology, smaller grains with sharp edges and a morphology resembling chinese scripts were also observed in the reference alloy. With a gradual increase in tungsten content to 0.05 wt. %, 0.10 wt. %, and 0.15 wt. % W (Fig. 4b, c, d), a consistent trend of decreasing occurrence of longer needle-like phases was observed, with their number and dimensions being almost eliminated at the highest tungsten addition (0.15 wt.% W). These undesirable needles were replaced by an increasing number of smaller, finer Fe-phase grains, especially in the chinese script morphology, which represents a favorable change in the microstructure. SEM imaging and subsequent EDX analysis (Fig. 4e, f) confirmed that the chemical composition of the needle-like phases corresponds to compounds with a predominance of iron and silicon. The observed increase in the proportion of Cu and Mg in close proximity to these needles suggests that Fe-rich phases, which crystallize early in the solidification process, serve as nucleation sites for the subsequent crystallization of copper- and magnesium-rich phases. Overall, the results show that tungsten acts as an effective morphological modifier that can transform the harmful needle-like morphology of Fe phases into less critical shapes, thereby potentially improving the overall toughness and ductility of the material. The results of line chemical analysis show that tungsten is present only in trace amounts, indicating its absence in the form of separate intermetallic phases and its dissolution in the material matrix.

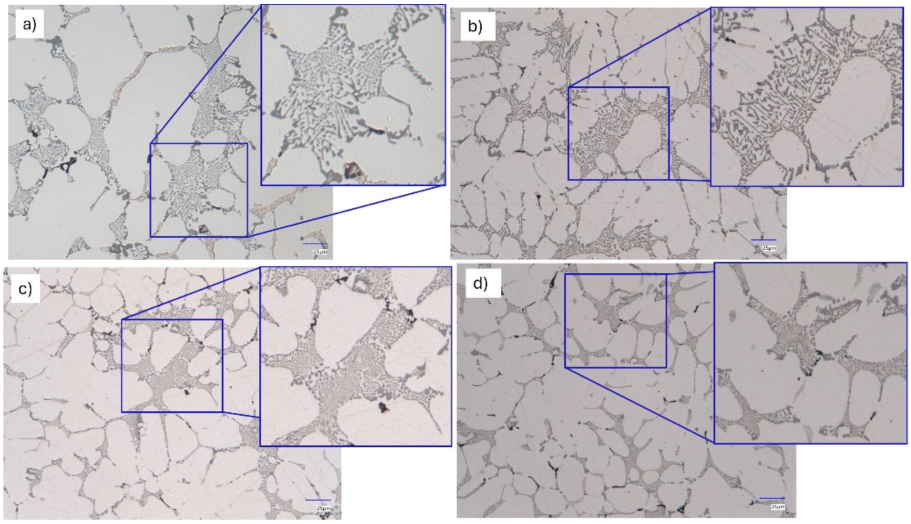

Fig. 2. Eutectic Si in experimental AlSi5Cu2Mg alloy in cast state: a) Ref. alloy; b) 0.05 W alloy; c) 0.10 W alloy; d) 0.15 W alloy

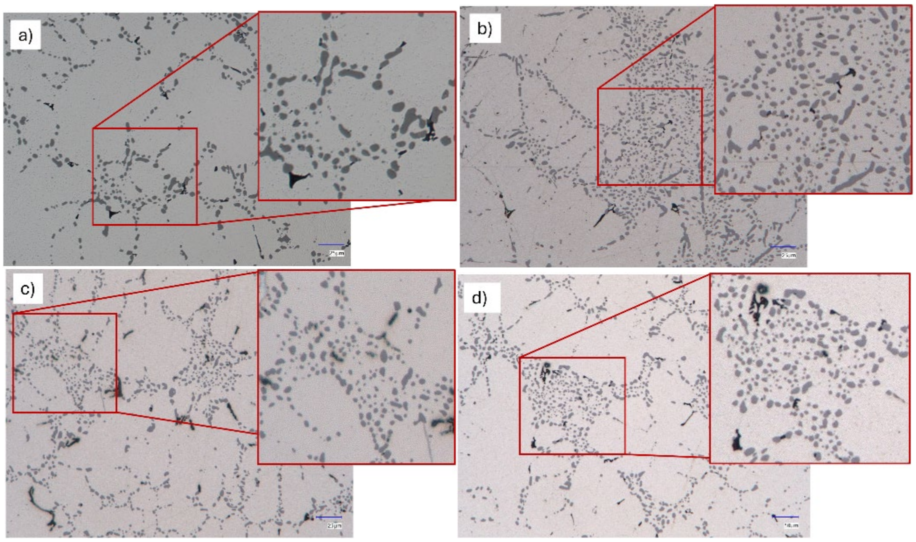

Fig. 3. Eutectic Si in experimental AlSi5Cu2Mg alloy after heat treatment: a) Ref. alloy; b) 0.05 W alloy; c) 0.10 W alloy; d) 0.15 W alloy

After applying the T7 heat treatment regime to the AlSi5Cu2Mg alloy, the microstructure of the iron-rich phases changed partially, although it retained its primary character from the cast state. In the reference alloy, a partial shortening of the needle-like Fe-phase formations was observed, as can be seen in Fig. 5a. This shortening is a direct consequence of the high temperature during the solution annealing phase, when the system attempts to reduce its total surface energy. At this temperature, the atoms are sufficiently mobile to allow diffusion, which leads to coagulation and spheroidization of unstable, needle-like Fe phases.

In alloys with higher tungsten content (0.10 and 0.15 wt. % W), similar to the cast state, Fe phases with sharp edges and a morphology resembling chinese script prevailed, while the needle-like morphology was eliminated with increasing amounts of W addition. This stability of finer morphology after the addition of tungsten indicates that the initial refinement in the cast state is so effective that it also significantly affects the resulting microstructure after heat treatment. The remnants of the permanently present needle-like morphology, as in the reference alloy, were eliminated by partially shortening their lengths (Fig. 5b,c,d).

In addition, EDX analysis revealed that the proportion of Cu and Mg in the Fe phases increased in all samples, suggesting that these phases could serve as sites for the precipitation and coagulation of other intermetallic phases (Fig. 5e,f). Overall, the transformation of needles into shorter and more compact shapes is important because it reduces stress concentrations and improves the conditions for increasing the mechanical properties of the material.

To better understand and visualize the effect of tungsten and heat treatment on the microstructure, the change in the morphology of iron-rich phases was quantified using two key parameters. The first is the maximum phase length (L_{max}), which provides a direct measure of the size and elongation of individual Fe phases, especially needle-like formations, which tend to adversely affect the mechanical properties of the material.

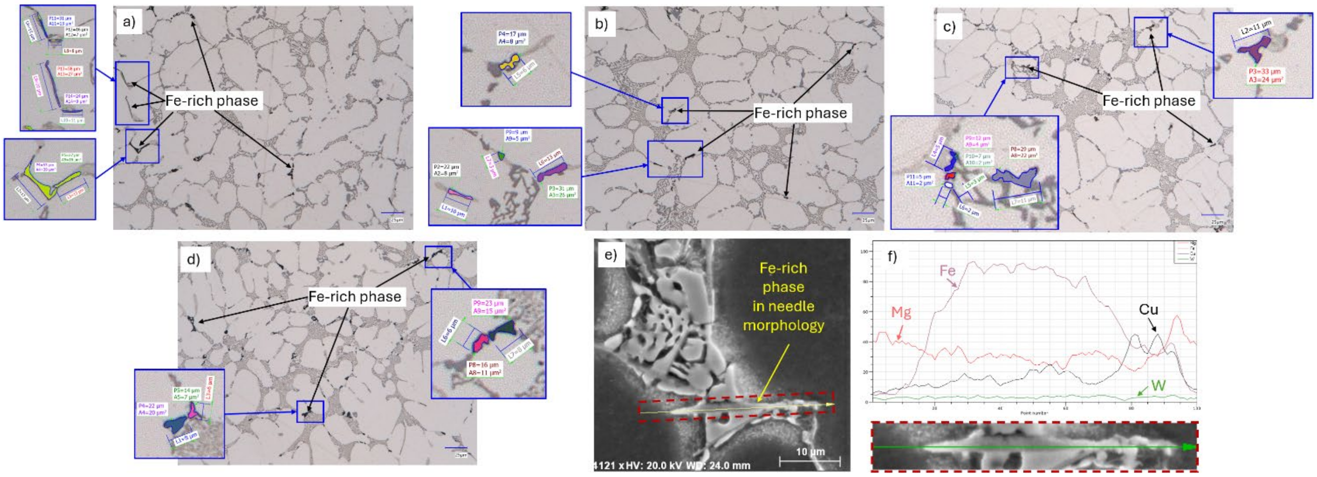

Fig. 4. Iron-rich phases in the experimental AlSi5Cu2Mg alloy in the cast state: a) Ref. alloy; b) Alloy 0.05 W; c) Alloy 0.10 W; d) Alloy 0.15 W, e) Detail of the distribution of intermetallic phases in the Ref. alloy, f) Line EDX analysis of the needle phase Al_5FeSi

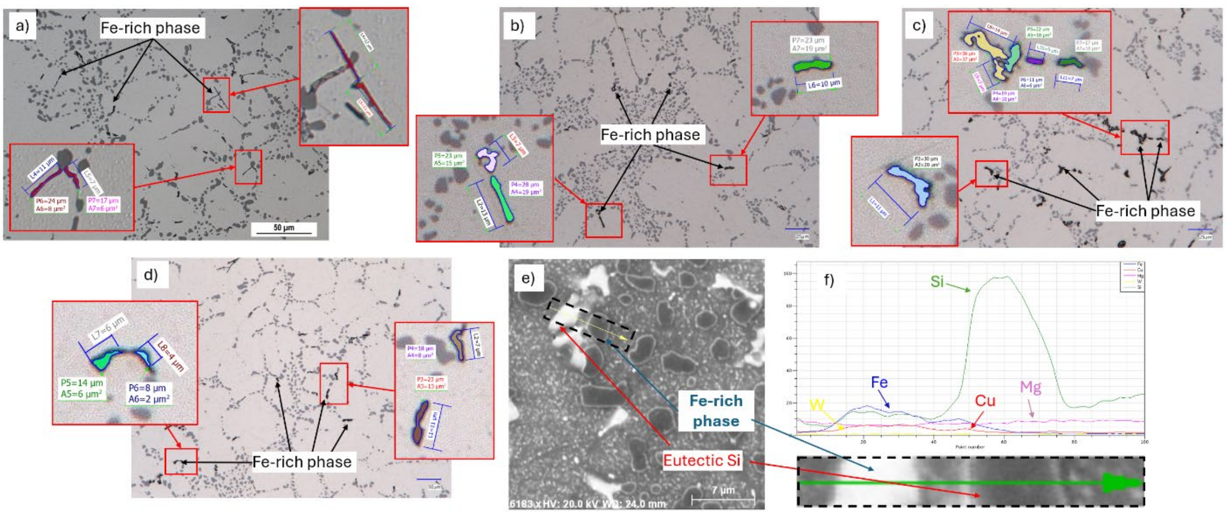

Fig. 5. Iron-rich phases in the experimental AlSi5Cu2Mg alloy after heat treatment: a) Ref. alloy; b) Alloy 0.05 W; c) Alloy 0.10 W; d) Alloy 0.15 W, e) Detail of the distribution of intermetallic phases in alloy 0.15 W, f) Line EDX analysis

The second parameter is Feret's diameter, specifically its maximum value ($Feret_{max}$), which is defined as the greatest distance between two parallel tangents to the particle contour. This parameter is useful for determining the total length of irregularly shaped particles because it provides a more comprehensive measure of size than linear length alone. In the case of non-spherical intermetallic phases, $Feret_{max}$ allows for a more accurate quantification of the transition from elongated, needle-like structures to more compact morphologies. The measured values, which reflect the average of multiple independent measurements taken to ensure statistical reliability, are displayed graphically in Fig. 6.

The quantitative analysis of changes in the morphology of intermetallic phases, shown in Fig. 6, demonstrates the strong refining effect of tungsten already in the as-cast state (AC). The reference alloy without tungsten addition (Ref. AC) shows the highest values of both monitored parameters (L_{max} = 14.4 µm and $Feret_{max}$ = 10.9 µm). These high values quantitatively confirm the presence of coarse, continuous β-Al_5FeSi needle-like particles. With a gradual increase in tungsten content (from 0.05 to 0.15 wt. % W), a significant and consistent decrease in both dimensional characteristics can be observed. The most significant reduction in the cast state was observed at a content of 0.15 wt. % W, where the L_{max} values decreased to 7.5 µm and $Feret_{max}$ to 6.1 µm. This nearly 50 % reduction in linear dimensions indicates that tungsten acts as an effective nucleating agent that suppresses the growth of long needles and promotes their fragmentation during solidification.

The application of T7 heat treatment (HT) further modifies the morphology of the Fe phases through diffusion processes. In the reference alloy (Ref. HT), there is a slight decrease in parameters due to the natural tendency for spheroidization and coagulation of phases at elevated temperatures. However, the most significant synergistic effect is observed when combining the addition of tungsten and the T7 regime. The lowest values in the entire experiment were measured for the alloy with 0.10 wt. % W after heat treatment (L_{max} = 7.4 µm and $Feret_{max}$ = 5.6 µm).

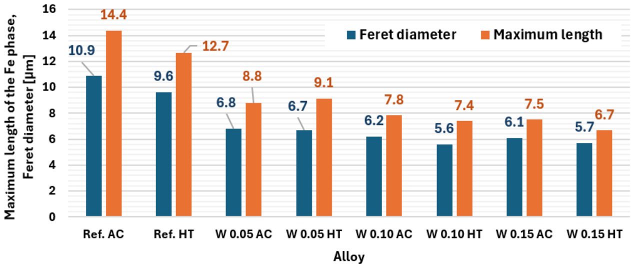

Fig. 6. Quantitative evaluation of the morphology of intermetallic Fe phases in AlSi5Cu2Mg alloys with tungsten addition and after T7 heat treatment

4. Conclusions

This study systematically investigated the individual and synergistic effects of tungsten microalloying and T7 heat treatment on the microstructure of a hypoeutectic AlSi5Cu2Mg alloy. The results confirmed that tungsten acts as an effective modifying and refining element that significantly improves the critical microstructural characteristics of the alloy. The following conclusions can be drawn from the results:

- The addition of tungsten in the concentration range of 0.10 to 0.15 wt. % acted as an effective grain refiner, resulting in a significant reduction of the Secondary Dendrite Arm Spacing index. This phenomenon is attributed to tungsten segregation at the solidification front, which induces constitutional undercooling and restricts dendritic growth.
- Tungsten served as a potent substrate for heterogeneous nucleation, promoting the transformation of eutectic silicon from a coarse morphology to a significantly refined and more compact structure already in the as-cast state.
- The addition of tungsten, alongside the T7 heat treatment regime, significantly accelerated the spheroidisation kinetics of silicon particles. At 0.15 wt. % W, an almost perfectly spherical morphology was achieved, driven by minimising total surface energy and enhancing diffusion paths in the pre-refined structure.
- Tungsten exhibited a strong modifying effect on the detrimental β-Al_5FeSi intermetallic phases. The traditional long acicular structures were successfully transformed into shorter, fragmented morphologies resembling "chinese script".
- The maximum refining efficiency was identified in the W 0.10 HT variant, where the lowest maximum phase length (L_{max}) = 7.4 µm) and Feret diameter ($Feret_{max}$ = 5.6 µm) were measured. This represents a reduction of almost 50 % in the linear and spatial dimensions compared to the reference alloy, which effectively mitigates stress concentrations within the matrix.

The results demonstrate that, when combined with the T7 regime, tungsten microalloying is a highly effective method of optimizing the microstructural integrity of AlSi5Cu2Mg alloy components subjected to high thermo-mechanical loads.

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