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Evaluation of changes of stereological parameters of eutectic phases in AlSiMg alloy after precipitation hardening

Ocena zmian parametrów stereologicznych faz eutektycznych w stopie AlSiMg po utwardzaniu wydzieleniowym

Abstract
Qualitative microstructure investigations of the AlSiMg alloy's microstructure in both its original state (with the characteristic primary structure) and after precipitation hardening revealed the significant heterogeneity of the eutectic phases concerning their shape, size, and distribution. An evaluation of the stereological parameters of the eutectic phases was carried out. The computer-image analysis was performed in order to define the fraction of the relative volume and shape of the eutectic phases and to establish their influence on the mechanical properties.

Keywords: qualitative analysis, AlSiMg alloys, stereological parameters

Streszczenie
Jakościowe badania mikrostruktury stopu AlSiMg, zarówno w stanie wyjściowym (o charakterystycznej strukturze pierwotnej), jak i po utwardzaniu wydzieleniowym, wykazały występowanie w badanym stopie istotnych niejednorodności faz eutektycznych pod względem kształtu, wielkości oraz rozmieszczenia.
W pracy przeprowadzono ocenę parametrów stereologicznych faz eutektycznych w stopie AlSiMg zarówno w stanie wyjściowym, jak i po utwardzaniu wydzieleniowym. Wykorzystując analizę obrazu komputerowego, określono udział objętościowy względnej faz eutektycznych oraz ich kształt, a także ustalono ich wpływ na właściwości mechaniczne.

Słowa kluczowe: analiza ilościowa, stopy AlSiMg, parametry stereologiczne

1. Introduction

Nowadays, changes in the automotive, aerospace, and military industry are occurring very quickly. Steel is consequently substituted by aluminum and titanium alloys [1].

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Despite the low mechanical properties of pure aluminum (R_m = 70–120 MPa), Al-based alloys are fortunately characterized by a favorable structural parameter (i.e., mechanical strength-to-density ratio), providing good material properties such as high tensile strength, fatigue limit, and corrosion resistance while simultaneously reducing the weight of the finished product (as compared to steel components). The desired properties of the material may be obtained by the appropriate selection of its chemical composition, optimizing the casting parameters and subsequent heat treatment [2] (precipitation hardening) or plastic deformation. The most-typical aluminum alloys are silumin enriched by silicon, which fosters good fluidity and small solidification shrinkage.

Hypoeutectic silumin containing between 4 and 11% silicon are the most-commonly-used foundry aluminum alloys [3]. They may be precipitation hardened thanks to the decreasing solubility of the alloying component in the matrix. It is well-known that, in AlSiMg alloys, the large eutectic phase particles (consisting mainly of pure Si) play a key role. Previous work [4] has shown that the occurrence of primary eutectic needle-shaped silicon phase precipitates has a negative effect on AlSiMg alloy load resistance, initiating the formation of microcracks. A correctly conducted precipitation hardening may have a positive effect on the mechanical properties of the alloy [4, 5]. The tendency for the material to degrade during operation is reduced by changing the shape of the phase precipitates as well as their globularization.

Elaboration of the quantitative property-microstructure relationship for AlMgSi alloys is very important from the point of view of its mechanical strength during exploitation. A field that allows the quantitative estimation of material properties is stereology, which provides information about a three-dimensional structure based on two-dimensional samples. Nowadays, computer image analysis largely has simplified the analysis of stereological data, being the main element of quantitative microstructure investigation.

As a result, a set of numbers describing selected features of the microstructure (e.g., the number of observed objects as well as their size, shape, and distribution) is defined. Basic stereological equations bind the spatial parameters of the structure with the values obtained during image analysis [6].

In this paper, an attempt was made to perform a computer image analysis in order to determine stereological parameters such as the shape factor and relative volume fraction of the eutectic phases in the AlSiMg alloy and correlate them with the mechanical properties of the tested material.

2. Methodology

The samples of the AlSiMg alloy, gravitationally cast into sand (a wall thickness of 10 mm) with the chemical composition shown in Table 1, were investigated in the present work. The chemical analysis was performed using a Spectrum 5M optical emission spectrometer.

Table 1. Results of chemical analysis of AlSiMg alloy (in wt.%)

Al	Si	Mg	Cu	Fe	Ti	Sr
89.7	7.8	0.5	1.4	0.5	0.01	0.10

The AlSiMg alloy was subjected to heat treatment in order to determine the influence of the initial microstructure as well as precipitation hardening on its mechanical properties (mainly yield strength). The supersaturation process was carried out at 540°C for 10 h/60°C_{H_2O} and aging at 200°C for 8 h/25°C_{air}.

The effect of heat treatment on the microstructure of the investigated alloy was analyzed using a Leica optical microscope equipped with data-acquisition software. Mechanical tests were carried out on the INSTRON 6025 universal-strength machine, upgraded by Zwick/Roell. An evaluation of the chemical composition in the micro areas was performed using an FEI Quanta 3D FEGSEM high-resolution scanning electron microscope (SEM) equipped with an EDS detector.

3. Results and discussion

Figure 1 shows an image of the AlSiMg alloy microstructure in the initial ("as-cast") state, and Figure 2 – after precipitation hardening. It should be noticed that the heterogeneity of the phase distribution is very important. It is observed that there are both eutectic-free areas and zones with their high density. The "as-cast" microstructure is characterized by the presence of elongated sharp-pointed needles of pure silicon. Heat treatment results in significant changes in the shape of the eutectic phases. Globularization and even coagulation in the silicon particles can be observed. This was also reported in paper [4].

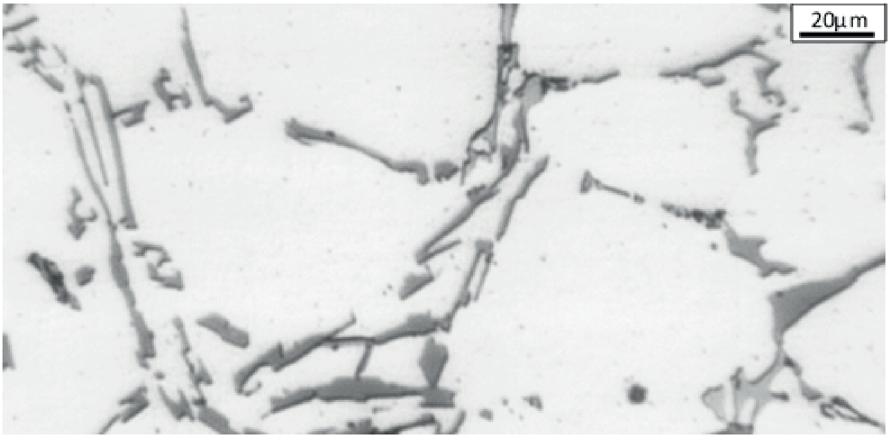

Fig. 1. Microstructure of AlSiMg alloy in "as-cast" state

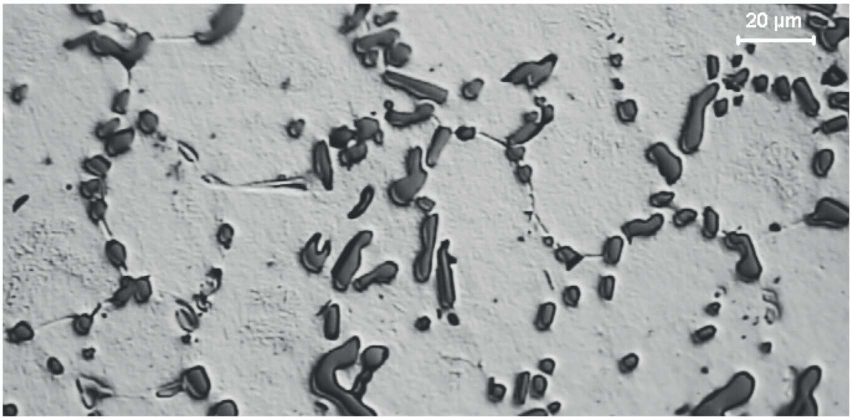

Fig. 2. Microstructure of AlSiMg alloy after precipitation hardening

Apart from the heterogeneity occurring in the AlSiMg alloy concerning the shape, size, and distribution of the eutectic phases, the segregation of silicon to the grain boundaries was also observed in micro-areas as revealed by SEM studies (Fig. 3).

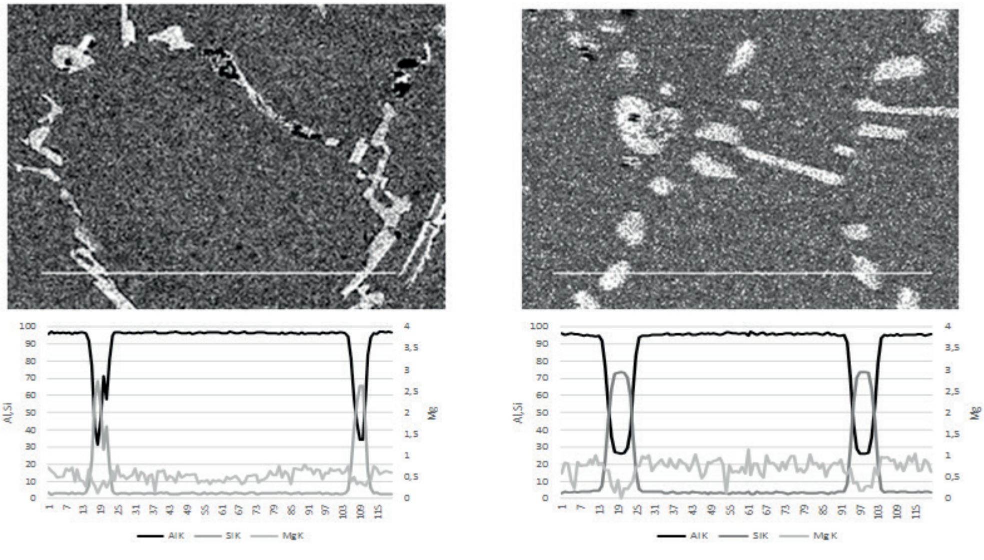

Fig. 3. Distribution of elements in matrix and separated eutectic phases

Due to the identified heterogeneity and complexity of the silicon phase morphology (especially in the initial microstructure), a quantitative evaluation was conducted through computer image analysis using Aphelion 3.2 (Copyright 1997–2004 ADCIS S.A.

and Amerinex Applied Imaging). This program allows us to determine the relative volume of the eutectic phase and its shape factor. Figure 4 shows a block diagram of the program used for analysis of a single image, and Figure 5 shows an example program dialog box.

The shape factor (kz), dimensionless and independent of the linear transformation, is given by Equation (1). It should be added that a minimum value of 1 is assumed for the disc object.

$$k_z = \frac{L^2}{4\pi S} \tag{1}$$

where:

L – perimeter of the object,
S – area of the object.

The COMPACTNESS factor (minimum values) was adopted as a criterion for evaluating the morphological changes of the eutectic silicon phases in the AlSiMg alloy subjected to precipitation hardening (Eq. (2)).

$$COMPACTNESS = \frac{16S}{L^2} \tag{2}$$

where:

L – perimeter of the object in the points of the image,
S – number of points belonging to the object.

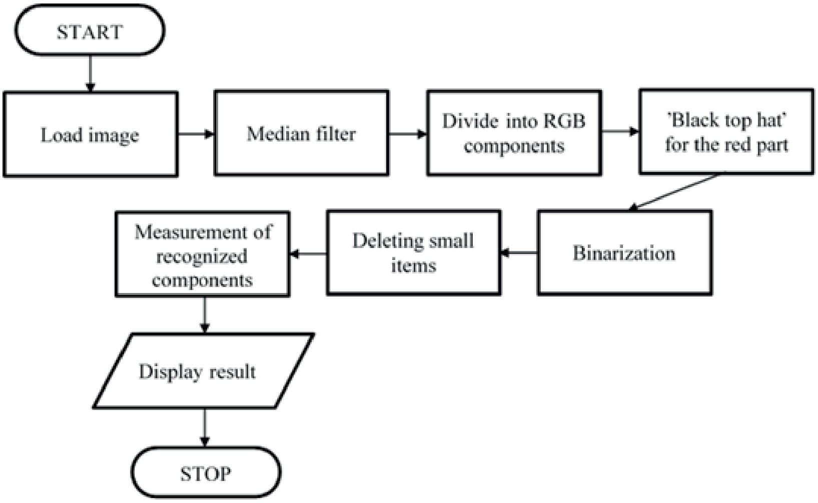

Fig. 4. Block diagram of applied analysis software for single image

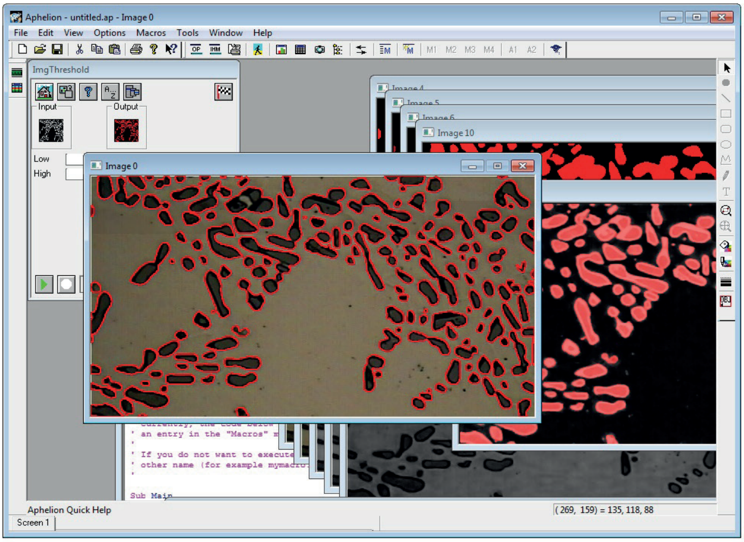

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Fig. 5. Example of Aphelion dialog window

The applied program enabled each time binarization (among others) in order to reduce the measurement error of the analyzed image. Sample images are shown in Figure 6 for the initial material and in Figure 7 for the alloy subjected to precipitation hardening. It is easy to see that the needle-shaped silicon phase takes a spherical form during heat treatment.

Fig. 6. Binarization of AlSiMg alloy microstructure in initial state using Aphelion software

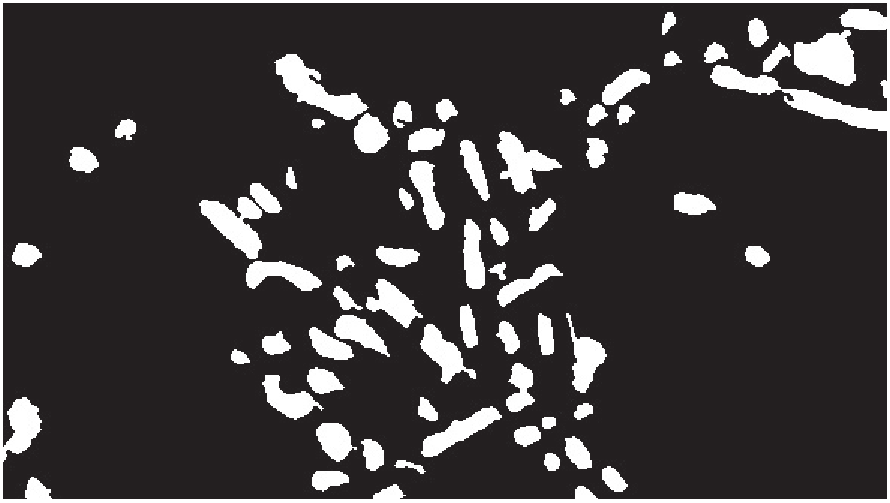
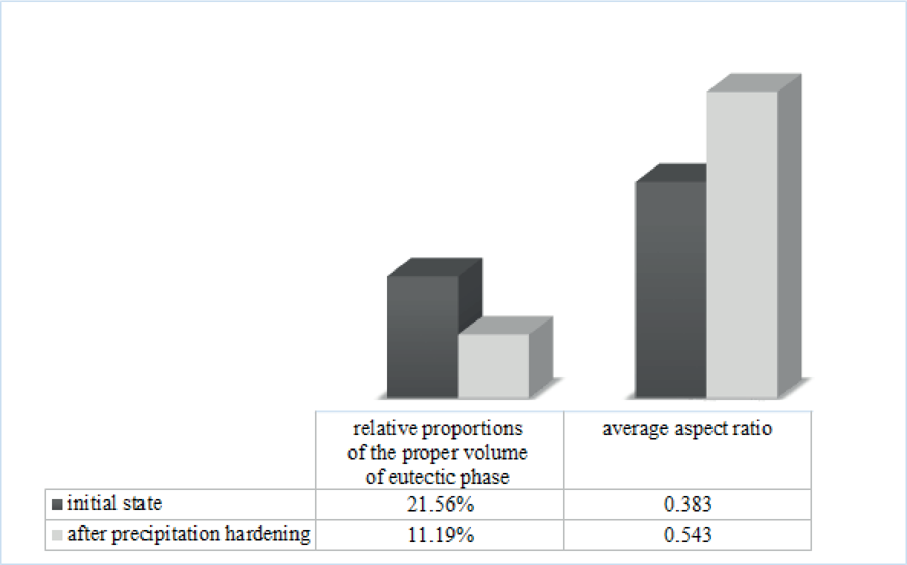


Fig. 7. Binarization of AlSiMg alloy microstructure after precipitation hardening using Aphelion software

The results obtained for the AlSiMg alloy analyzed for the relative volume fraction of the eutectic phases and shape factor are shown graphically in Figure 8.



	relative proportions of the proper volume of eutectic phase	average aspect ratio
■ initial state	21.56%	0.383
□ after precipitation hardening	11.19%	0.543

Fig. 8. Relative proportions of the proper volume of the eutectic phase and the average aspect ratio in AlSiMg alloy, initial state and after precipitation hardening

The effect of the precipitation hardening on the mechanical properties of the AlSiMg alloy was determined in the Static Compression Test; the results are shown in Figure 9.

It can be seen from the analysis of the yield point curve that the suitably performed heat treatment processes (quenching + ageing) resulted in the increase of R_{plc} in the material to be tested.

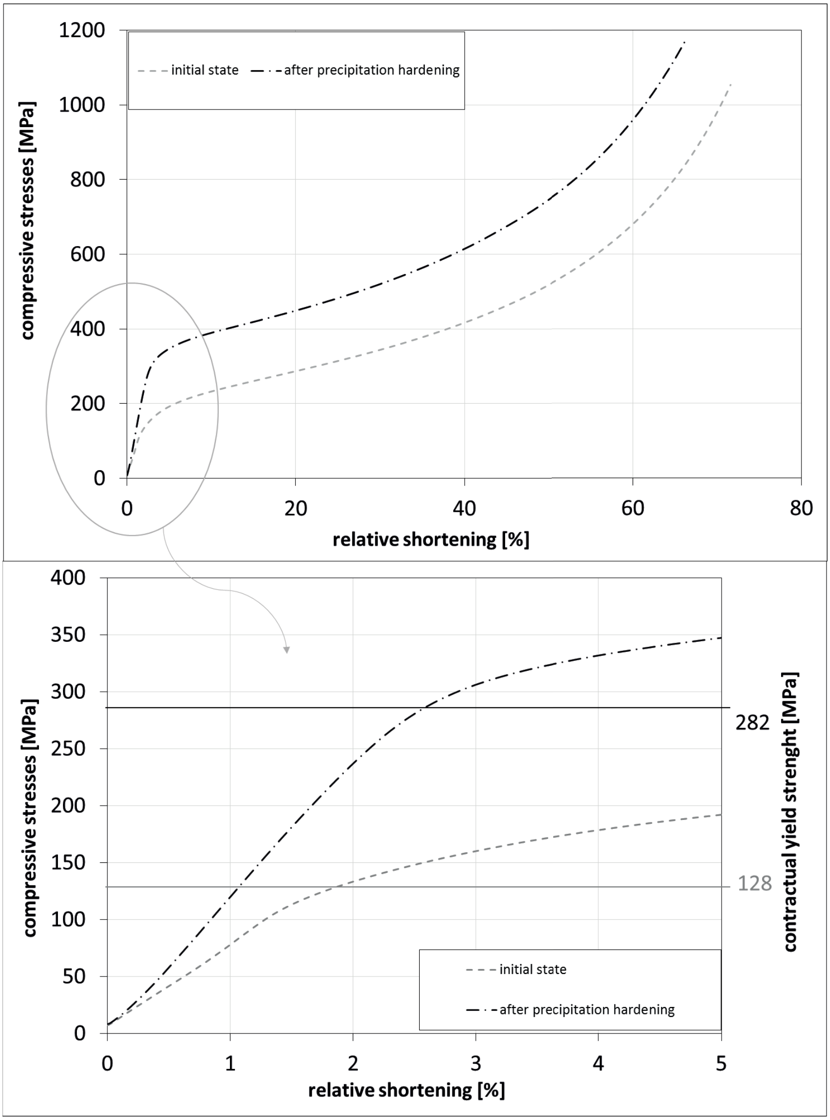


Fig. 9. Results of Static Compression Test

4. Summary

A comprehensive qualitative assessment of the eutectic phase precipitates present in the microstructure of the AlSiMg alloy (both in the initial “as-cast” state and after individual heat treatments) could not be the basis for the elaboration of correlation between the description of the eutectic phase and the physical, mechanical, and utility properties. The use of Aphelion 3.2 software allowed us to create a database of the characteristic stereological components of the microstructure present in the AlSiMg alloy after various technological steps. The created database is the basis for determining the correlation between the microstructure and the alloy properties as well as the information needed to simulate the phenomena characteristic for these alloys without the need for tedious and time-consuming metallographic quality studies.

Acknowledgement

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