Comparison of mechanical behaviour of microstructures of 2024 aluminium alloy containing precipitates of different morphologies

Anna Staszczyk¹ and Jacek Sawicki¹

¹Institute of Materials Science and Engineering, Lodz University of Technology, Stefanowskiego 1/15, 90-924 Lodz, Poland

Email: jacek.sawicki@p.lodz.pl

Abstract. The phenomena occurring in the microstructure of the material are responsible for its macroscopic properties, such as strength, hardness, and toughness. Strengthening phases with the appropriate composition and characteristics increase the strength of the alloy. However, excess brittle intermetallic phases may cause problems with cracking and plasticity of the material. The amount and morphology of those particles are related to the chemical composition of the alloy. Simulation of tensile loading of the microstructure of three different 2024 aluminium alloys shows how the distribution of intermetallic phases affects stress states in the material. The results show that variations in the amount of the alloying additions in the range described by the standard can influence the deformation mechanisms in the material.

1. Introduction

Aluminium alloys of Al-Cu-Mg system are popular because of their good mechanical properties and low density [1]. Their strength and hardness depend strongly on the microstructure being the product of multi-stage heat treatment, typically solution treatment followed by artificial aging. There are several aspects in the microstructure of an alloy that has to be taken into consideration while predicting its mechanical properties. There are many different types of particles that can form during heat treatment; while some of them have a strengthening effect, the others can contribute to brittle fracture of the material.

Several works focus on the complexity of the microstructure of 2024 alloys. Multiple alloying additions contribute to the formation of many intermetallic phases with varying chemical compositions. Silicon and iron have poor solubility in the alpha solution of an Al-Cu-Mg alloy. They form intermetallic phases with copper, magnesium, and manganese during solidification of the cast. It is not possible to dissolve them entirely during solution treatment, and they do not change during further heat treatments in elevated temperatures. Boag et al. described presence of multiphase, composite particles in 2024-T3 material [2]. Mrówka-Nowotnik and Sieniawski examined precipitates of phases present in the microstructure just after casting [3]. Shabestari et al. examined the formation of those intermetallic compounds in 2024 alloy during solidification with different cooling rates [4].

The intermetallic particles are usually much harder and more brittle than the matrix or S phase, as measured by Radutoiu et al. [5]. They also act as the initiators of localised corrosion as proved by DeRose et al. [6]. Multiphase precipitates in 2024 alloy with morphology resembling core and shell were subject of works by Kaczmarek [7][8] and Lipa [9].
In this work, the authors expand the existing method for determining the tensile behaviour of a heterogeneous alloy microstructure. The numerical algorithm has been previously described in other papers [10][11][12] and is based on a combination of the cellular automata method with digital material representation.

2. Materials and methods
The materials used for this study were rods of three 2024 alloys obtained from different suppliers with varying chemical compositions (shown in Table 1). The considerable difference can be observed in the amounts of silicon and iron present.

The specimens cut from the rods were subjected to the heat treatment processes, solution treatment at 500°C for 4h, and artificial aging at 180°C for 10h. The process parameters were designed so that they follow the most popular procedures applied in industrial settings. For reference, the Vickers hardness was measured for all three alloys on Innovatest Verzus 700AS (Table 3). All of the alloys had similar hardness.

Table 1. Chemical composition of the examined alloys.

| Alloy | Cu   | Mg   | Mn   | Si   | Fe   | Zn   | Ti   | Al   |
|-------|------|------|------|------|------|------|------|------|
| A     | 4.76 | 1.36 | 0.79 | 0.16 | 0.12 | 0.04 | 0.02 | Rest |
| B     | 4.15 | 1.51 | 0.64 | 0.24 | 0.25 | 0.09 | 0.06 | Rest |
| C     | 4.39 | 1.62 | 0.74 | 0.41 | 0.43 | 0.04 | 0.05 | Rest |

The samples were examined on the Scanning Electron Microscope, Jeol JSM-6610LV. The images of microstructures were all taken with 1000x magnification. The observed phases were additionally examined with Energy Dispersive Spectroscopy to identify their chemical composition. Two main types of precipitates were observed; round ones and those of more irregular shapes. The round dispersoids were only found in the alloy A and had only Al and Cu or additionally Mg in them. The rest of the intermetallic particles contained Cu, Mn, Fe, Si, and Mg in different proportions.

Figure 1. Example of the phase identification in the alloy A.

Mechanical properties (hardness and elastic moduli) of observed phases forming the precipitates as well as the particle-free zones were measured with the use of G200 nanoindenter (MTS Nano...
Instruments). The Young’s modulus of the matrix (measured at random places between precipitates) was the same for all of the specimens and was around 90 GPa. The round precipitates with Cu and Mg had the average modulus close to 120 GPa, while the big irregular particles had the average modulus of 160 GPa. Those mean values were later used in the simulation.

| Table 2. Elastic modulus of examined phases in the microstructure of alloys. |
|------------------|------------------|------------------|
|                 | Matrix           | Round precipitates | Other precipitates |
| Young’s modulus [GPa] | 90               | 120              | 160              |

| Table 3. Vickers hardness of examined alloys. |
|------------------|------------------|
| Alloy           | Hardness in T6 state |
| A               | 138 ± 2.7 HV      |
| B               | 134 ± 1.9 HV      |
| C               | 135 ± 3.2 HV      |

For the calculational purposes, the images were subjected to post-processing. The goal was to feed the algorithm with a domain where the phases of one type are one colour and distinguishable from the matrix. The algorithm than associates the colour of the pixels with a certain value of the Young’s modulus measured from the nanoindentation test. The program simulates the tensile loading of the two-dimensional domain when it is subjected to 0.05% deformation. The outcome of the simulation is a colour map showing the von Mises Equivalent stress in the microstructure.

![Figure 2. The microstructure images of the alloys A, B and C used in the simulation.](image)

3. Results and Discussion
The microstructure of the alloy A contains two main types of precipitation exhibiting visual distinction. Some of them are round in shape and have been identified with EDS as θ or S phases (Al2Cu or Al2CuMg). Precipitates of such stoichiometry are usually encountered on smaller length scales and are believed to be responsible for strengthening mechanisms. Here, observed particles are notably larger, with dimensions up to 5µm. It is important to note that such precipitates were not observed in two other alloys. Nanoindentation results show that they are slightly less hard than the rest. That confirms a similar conclusion obtained by Radutoiu et al. [13]. The microstructure fragment chosen for simulation contains the same amount of both particle types.

The particles in alloy B are much larger and have rather irregular complicated shapes. It is common for them to form circles surrounding small areas of the matrix. Such precipitates are often referred to as
The “Chinese script”. Their sizes can go up to 50μm. Since they are large and brittle, they crack easily, which can be observed in the examined specimens as a result of grinding and polishing of the surface as the decomposition of the precipitate into smaller fragments. The microstructure chosen for simulation contains the typical particles, one of them being visibly cracked and one of them having a “hole” in the centre. It is assumed that those are all precipitates of the same phase.

The microstructure of the alloy C is much more dispersed and consists of many smaller precipitates of the hard intermetallic phase with lengths up to 10μm. They were identified to be Al(CuMnFe) phases, occasionally containing Si, which is similar to the bigger phases in alloys A and B.

Figure 3. Results of the simulation of the tensile loading of the microstructure. The equivalent stress states are shown for alloys A, B, and C.

The overall mechanical properties of an aluminium alloy depend on the combination of effects caused both by large dispersoids and small second-phase particles present in the microstructure. The amount of them, their composition, and morphology change depending on the amount of the alloying elements in the material. In this case, the overall amount of the intermetallic phases was similar for all of the three alloys. However, there was a considerable difference in dispersion of the particles that were
observed in SEM photos. The simulation results show that the highest stresses concentrate on the edges of precipitates. The highest stress was obtained in one of the large precipitates of the alloy B. It shows that the narrow parts of the hard precipitate are subjected to large stresses, which in real life may result in the crack initiation. The lowest maximum equivalent stress was obtained for the alloy A. However, the distribution shows the concentration points on the verges of the harder precipitates again. In this case, the round precipitates have less influence on the stress state than the others. The most uniform distribution is shown for the alloy C. It correlates with the generally more uniform distribution of precipitates and their dispersion.

In conclusion, the numerical simulation of the tensile loading of the microstructure of the Al 2024 alloy showed considerable differences in stress states between alloys with different chemical compositions. The simulation was based on the experimental measurements of mechanical properties of intermetallic phases. The results showed that amount of alloying elements has an influence of size and dispersion of intermetallic particles, and in some cases, on their type. More dispersed distribution results in more uniform equivalent stress state in the material. On the other hand, when particles are large and very hard they tend to concentrate high-stress values on their edges, which may result in cracking.

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