Influence of additional elements (Si, Ti and B) on the microstructure, mechanical properties and castability of aluminum alloys (A201)

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Abstract. Improving the castability, mechanical properties and modifying the microstructure of the A201 alloy (Al - 4.97wt. % Cu – 0.56 wt. % Ag) were done by adding Si, Ti and B elements. The four alloys of A201 with additions of: (1) Si, (2) Ti and B, (3) Si, Ti and B, (4) non, were investigated in the as-cast, solution treated at 550°C for 20 hr and aged at 170°C up to 32 days conditions. Combination of different microscopes (HRSEM/EDS, TEM) and microhardness tests were used to investigate how the alloy properties influenced by the precipitation. Additions of Si resulted in the grain coarsening and an increase in the amount of near-grain boundary secondary phases. Additions of Ti and B resulted in the grain refinement, prevented hot tears, but caused a large amount of Al₃Ti phase which makes the melt more viscose, and less fluid and castable. The mechanisms of the influence were recognized as facilitating the GP zones nucleation: Si atoms provide more probable homogeneous nucleation of the <001>ₐ GP zones transforming to θ° phase during aging; TiB₂ particles serve as the sites for heterogeneous nucleation of <111>ₐ GP zones which then transform to Ω phase. The precipitation sequence during aging was the following: SSSS → GP zones → θ° + Ω → θ° + Ω → θ° → θ. The maximum microhardness was achieved with two kinds of semi-coherent precipitates in the structure: θ° (Al₃Cu- tetragonal) and Ω (Al₃Cu-orthorhombic). Therefore, joint additions and corresponding thermal treatment can provide optimal microstructure and mechanical properties of the A201 based alloys.

1. Introduction

A201 alloy used in aerospace and automobile parts due to its good properties and easy of production [1-6]. Solution treatment followed by aging cause the decomposition of Supersaturated Solid Solution (SSSS) to different precipitates: GP zones → θ° → θ° → θ and it is depending on the degree of supersaturation and the aging temperature [1-3, 7-12]. The process and/or kinetics of precipitation can be changed by adding a small amount of alloying elements [1, 2, 9, 13].

For the Al alloys, it was investigated the effect of different elements additions on the mechanical properties [13-17]. The addition of Si controls the amount of eutectics structure of Al-Si and also influences the precipitation sequence. Additions of Ti and B cause the grain refinement of the primary Al phase. However, the cross and mutual influence of alloying elements is not fully understood.

In the present work, the following alloys were investigated: (1) Al201 (referred hereafter as Base alloy – BA), (2) BA+1 wt. % Si, (3) BA+1.33 wt. %B= 3.17 wt. % Ti and (4) BA+1 wt. % Si +1.33 wt. %B+ 3.17 wt. % Ti al. These compositions were selected to achieve improved properties and castability. They were investigated by a combination of high resolution scanning electron microscopy (HRSEM), energy dispersive X-ray spectrometry (EDS) and transmission electron microscopy (TEM).
Microhardness measurements were performed by a Vickers hardness tester to reveal the effect of precipitation on the mechanical properties of the alloy.

2. Experimental
The chemical composition of the A201 alloy (alloy I) is given in table 1. The nominal compositions of the prepared alloys (II, III and IV) are given in the table 1.

Table 1. The compositions (in wt. %) of the investigated alloys.

| Alloy | Nominal composition               |
|-------|-----------------------------------|
| I     | BA: 4.97wt. % Cu-0.56wt. % Ag-0.33wt%Mn-0.24wt. %Mg |
| II    | BA with addition of 1 wt. % Si    |
| III   | BA with additions of 1.33 wt. %B and 3.17 wt. % Ti |
| IV    | BA with additions of 1 wt. %Si, 1.33 wt. %B and 3.17 wt. % Ti |

For detailed experimental procedure refer to [13].

3. Experimental results and discussion
Castability and mechanical properties of the alloys after ST and aging were investigated together with comprehensive investigation of the alloy’s microstructure.

3.1. Castability
To check the fluidity and castability of the alloys, a metal die with three plates having different thicknesses was used. The ability of the cast to fill in was used to evaluate the castability. The additions of Si to A201 alloy have been shown to increase castability of the alloy [13]. However, samples with addition of 1wt. % Si contained a lot of cracks (figure 1(b)). The additions of Ti and B allowed to avoid the presence of cracks (figures 1(c) and 1(d)), but made the melt more viscous, and as a result, the fluidity and castability of the as-cast alloys decreased.

Figure 1. Castability tests for the four alloys cast into a metal die with three plates of different thicknesses: (a) A201, (b) A201-1 wt. % Si, (c) A201-1.33 wt. %B- 3.17 wt. % Ti and (d) A201-1 wt. % Si -1.33 wt. %B- 3.17 wt. % Ti.

3.2. Age hardening behavior
The hardness Vs time curves of the four investigated alloys during isothermal aging at 170°C for up to 32 days are presented in figure 2. It was decided that the aging temperature should be 170°C, since it was mentioned by Gergi [18], that the early stages precipitates do not appear at higher temperatures (above 180°C) of aging.
Figure 2. Hardness Vs time curve of the four alloys aged at 170°C; the error bars of 5 HV.

For all investigated alloys microhardness reached a maximum value after a certain aging time, and then further aging led to its decrease (overaging). For alloys I and II (A201 and A201-1 wt. % Si) the maxima (~138 HV and ~155 HV, respectively) were reached after ~6 h of aging; For alloys III and IV containing Ti and B the maxima (~147 HV and ~162 HV, respectively) were reached after 1 day of aging.

3.3. Microstructure

Figure 3. Backscattering (AsB detector) HRSEM micrographs of the as-cast alloys; (a) BA, (b) BA+1 wt. % Si,(c) BA+1.33 wt. %B+3.17 wt. % Ti and (d) BA+1 wt. % Si +1.33 wt. %B+3.17 wt. % Ti alloys.

3.3.1. As-cast alloys. As can be seen from HRSEM micrographs (figure 3), the as-cast alloys consisted mainly of the α-Al phase as a matrix and eutectic structures (α-Al/θ-Al2Cu) in the near grain boundary regions. Alloys III and IV, with Ti and B additions, (figures 3(c) and 3(d)), contain also hundred microns size particles having two different shapes: needle-like and round-like particles. The composition of both the needle-like and round-like particles, was measured by EDS HRSEM analysis, and was found to be close to Al3Ti.
3.3.2. Aged alloys: microstructure and phase composition. Several samples of the aged alloys were selected for detail microstructure investigation: after aging periods of 30 min and 3 hr (under- aged), 6 hours and 1 day (maximum peak-aged).

- Under-aged samples (first peak after 30 min)

As seen from the HAADF STEM images of the alloys II and III in the under-aged condition (figure 4), the microstructures contained very thin disc-shape precipitates with diameters about 2–10 nm, elongated along two perpendicular directions, which are identified as GP zones. Two types of GP zones were recognized: (i) elongated along <001>α directions and (ii) elongated along <111>α directions.

- Maximum peak-aged samples (6 hours / 1 day)

Typical TEM image and corresponding SAED pattern of the four investigated alloys aged for 6 hr (alloys I, II) and for 1 day (alloys III, IV) are presented in figure 5, with zone axis [112]α. As seen from the images, the microstructure in the peak-aged condition contained two kinds of precipitates which can be recognized as θ' and Ω phases. The platelet-like θ' (Al2Cu, tetragonal, semi-coherent) precipitates are extending along <001>α direction, while Ω (Al2Cu, Orthorhombic, semi-coherent) precipitates are extending along <111>u.

4. Discussion

In order to understand how the Si addition influences the precipitation process, the EDS analysis was performed on the GP zone in the alloy II (A201-1wt% Si) after 30 min aging, it was found that increased amount of Si atoms is present along the GP zone.

The alloying of the BA with Ti and B increases the Ω phase precipitates. This result can be explained by heterogeneous nucleation of <111>α GP zones on the TiB2 particles. As was shown by [19], the activation energy for the Ω phase nucleation was greatly reduced by the addition of TiB2 and silver, and the TiB2 particles were even more effective than Ag.

The θ' precipitates are thermodynamically more favorable than θ'' and Ω phases. That is why they grow during following aging in the expense of existed θ'' and Ω precipitates.
5. Conclusion
The additions of silicon, titanium and boron to the A201 alloy can improve the alloy properties by proper modification of the microstructure. The Si addition alone may improve castability and increase the microhardness, however, it results in grain coarsening and increase amount of the secondary phases in the grain boundary regions. On contrary, the additions of Ti and B resulted in the grain refinement, prevented hot tears, but caused a large amount of Al₃Ti phase making the melt more viscose, less fluid and castable. The mechanisms of the influence were recognized as facilitating the GP zones nucleation: Si atoms provide more probable homogeneous nucleation of the <001> GP zones transforming to θ'' phase during aging; TiB₂ particles serve as the sites for heterogeneous nucleation of <111> Ω GP zones which then transform to Ω phase. The precipitation sequence during aging of the (A201+Si+Ti+B) alloy was the following: SSSS → GP zones → θ'' + Ω → θ' + Ω → θ → θ'. The maximum microhardness was achieved with two kinds of semi-coherent precipitates in the structure: θ' (Al₃Cu- tetragonal) and Ω (Al₃Cu-orthorhombic). Therefore, joint additions and corresponding thermal treatment can provide optimal microstructure and mechanical properties of the A201 based alloys.

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