THE EFFECT OF VANADIUM ADDITION ON STRUCTURE AND MATERIAL PROPERTIES OF HEAT TREATED 6XXX SERIES ALUMINIUM ALLOYS

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Abstract

The paper presents the results of the mechanical properties of AlMgSiCu aluminum alloys with vanadium in an amount of 0.1 and 0.2 wt.%. During solutioning heat treatment and aging which were compared with those for the material without the addition of copper. The reference material was 6xxx alloy without copper and vanadium. Analysis of the structure of the transmission electron microscope (TEM with EDS) revealed the role of vanadium in the heat treatment process.
During the aging, in addition to precipitation of the phases Al_2Cu and Mg_2Si, the finely vanadium and vanadium-iron phases was observed. The size and distribution vanadium phases were also dependent on the chemical composition of the alloy. It was found that in AlMgSuCu alloys with vanadium clearly relies Rm and Rp0,2, the additive vanadium in an amount of 0.2 wt.%. increases elongation almost doubled. The optimum heat treatment parameters was determined for states T6, T61, T64 and T7.

The information on the role of vanadium in the process of strengthening of precipitation are sporadic [3-6]. It is only known that vanadium acts as a grain refiner and also lowers the conductivity and raises the temperature of recrystallization [4,5]. Investigation of the effect of vanadium in an amount of 0.1% in the alloy 6063 [6] found that the kinetics of vanadium accelerates precipitation of phase β 'and β", which in turn will have an impact on strength and yield strength of the material after aging.

Introduction

In connection with the EU Energy Efficiency Directive, including fuel efficiency regulation, various solutions are searched to reduce energy consumption, also by reducing the weight of vehicles. Therefore, a growing number of automotive parts is made from light metal alloys, mainly based on aluminium and magnesium. The materials from which these parts are produced are characterized by different properties, depending on the chemical composition and heat treatment parameters.

Owing to their properties, aluminium alloys are widely used in the transport industry. The possibility to control these properties, among others, also by changes in the chemical composition, processing route, or heat treatment allows these materials to be used for the increasing number of vehicle components.

The goal most important in the construction of a vehicle is its safety, and in particular the behaviour during accidents. Accidents are simulated in the, so called, "crash tests". Detailed analysis of the behaviour of materials undertaken in such studies allows selecting the best design of an element, as well as a modification of its properties through changes in the chemical composition and heat treatment parameters. The choice of material for parts operating in the crumple zones during accidents should allow not only for the mechanical properties of the alloy, but also for its ability to absorb energy.

Evidence exists that wrought aluminium alloys containing vanadium in a range of 0.05 - 0.5% possess not only high mechanical properties and high ductility, but also the ability to absorb the kinetic energy [1-2].

The information on the role of vanadium in the process of precipitation hardening is but very scarce [3-6]. It is only known that vanadium acts as a grain refiner, reduces the conductivity and raises the temperature of recrystallization [4,5]. Studies of the vanadium effect when added in an amount of 0.1% to 6063 alloy [6] have proved that vanadium accelerates the precipitation kinetics of the β 'and β" phases, which in turn will have an impact on the tensile strength and yield point of the material after aging.

The aim of this study was to determine the effect of vanadium and copper additions on the mechanical properties of 6xxx series alloys after heat treatment, and to establish the optimum time and temperature parameters of the aging process to obtain alloys in the T6, T61, T64, and T7 condition.

Experimental

Tests were performed on samples extruded from Φ100mm ingots [8] (Table 1). The maximum vanadium content was 0,2wt% and all vanadium occurred in the ingot matrix. In the structure of ingots and in extruded rods, the presence of the intermetallic phases of the Al_3V and $Al1_8Mg_3V_2$ type was not detected [9-12]. The maximum solubility of vanadium in aluminium is 0.27wt% [13].

Table 1. Characteristics of the test material

Sample symbol	V content [%weight]	Alloy composition
V0	0	AlSiMg
V02	0,2	AlSiMgV02
RV01	0,1	AlSiMgCuV0,1
RV02	0,2	AlSiMgCuV0,2

Samples cut out from rods were subjected to heat-treatment, which consisted in solutionising at a temperature of 530°C for 2 hours, followed by aging at 175°C for 2 to 64 hours. After the successive stages of solutionising and aging, the hardness of the samples was measured. The results are in Figure 1.

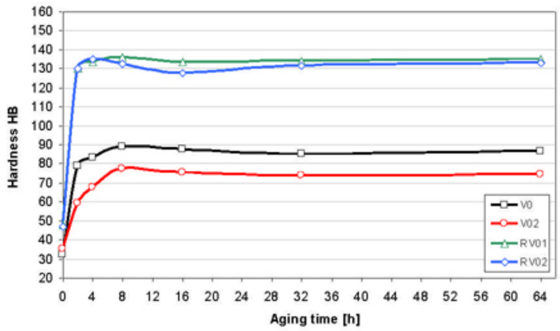


Figure 1. Aging curves (hardness) for 6xxx alloys with V and Cu+V

For 6xxx series alloys, i.e. with and without copper, regardless of vanadium content, the maximum hardness was achieved after about 8 hours of aging at 175°C. Longer aging caused only a slight decrease in hardness. On the other hand, a fundamental difference in hardness was observed between the groups of 6xxx series alloys with vanadium, and with vanadium and copper. The addition of vanadium to a 6xxx series alloy reduced hardness even in respect of the alloy in the starting condition. The addition of vanadium and copper to a 6xxx series alloy increased hardness by more than 40%, this value being the highest for the 0.2% vanadium addition. It was also found that the increasing vanadium content caused a decrease in alloy hardness.

Based on the hardness aging curves, for testing of the mechanical properties, samples aged for 4, 8, 16 and 64 hours were selected.

Alloy properties were determined from the static tensile test and upsetting test. The static tensile test was performed on an Instron 5582 testing machine at ambient temperature applying the strain rates of 2mm/min. The compression test was performed on an Instron 600DX machine at ambient temperature at a rate of 5mm/min.

Structure examinations and chemical analysis were performed on the Tecnai G2 transmission electron microscope with STEM attachment, HAADF detector (High-Angle Annular Dark Field detector) and EDS analyser. Thin foils were prepared by grinding and electropolishing and, in the case of samples with Cu, using the "cleaning" option in a RES 101 ion dimmer.

Microstructure of the 6xxx alloys with vanadium was examined on:

- as-extruded samples (state F) – RV01 and RV02,
- samples after solution heat treatment – V0, V02 and RV02,
- samples after 4h aging (state T64) – V0, V02 and RV02,
- samples after 64h aging (state T7) – V0, V02, RV01 and RV02.

Results

Mechanical tests

The effect of aging time on the mechanical properties of alloys is shown in Figures 2-4.

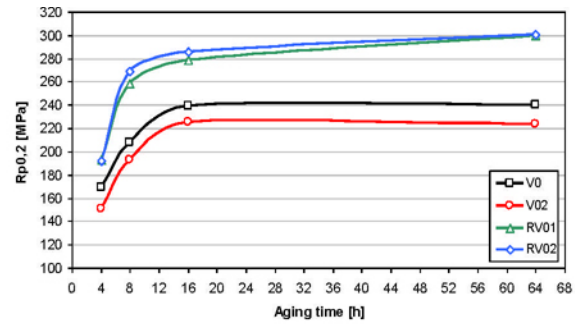


Figure 2. Yield strength determined in a tensile test for alloys after the aging treatment

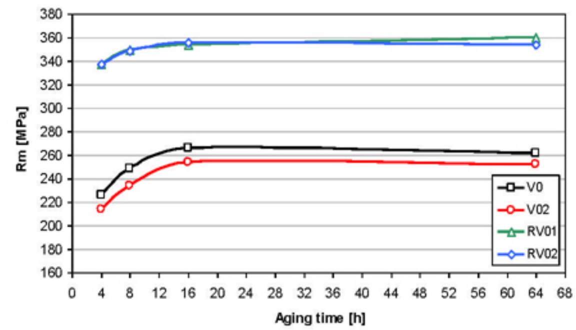


Figure 3. Tensile strength determined in a tensile test for alloys after the aging treatment

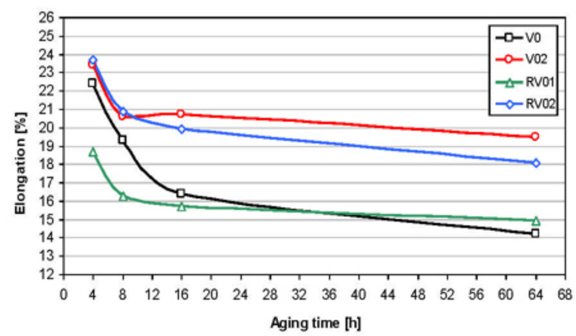


Figure 4. Elongation determined in a tensile test for alloys after the aging treatment

Similar to hardness changing in the alloy in function of its composition, also the yield strength and tensile strength were changing. Compared with the base AlSiMg alloy, the addition of vanadium to a 6xxx series alloy reduced both the yield strength and tensile strength. Copper and vanadium additions to the base alloy resulted in a significant increase of the yield strength and tensile strength. The highest mechanical properties were obtained in the alloy containing 0.2% vanadium. It is interesting to note that the values of elongation were similar for both alloys, i.e. with and without copper but were significantly higher in alloys with vanadium.

The effect of aging time on the mechanical properties in compression test is shown in Figure 5.

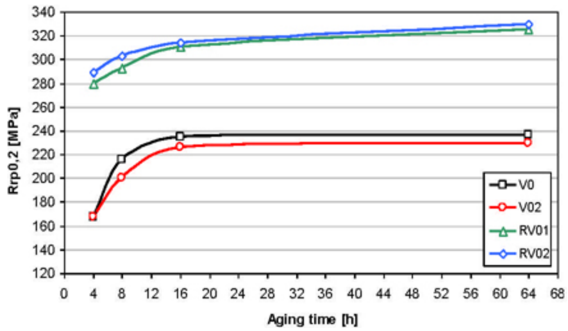


Figure 5. True yield stress determined in the compression test for alloys after the successive stages of an aging treatment

Changes of the true yield stress, determined in the compression test for alloys after the successive stages of an aging treatment, were similar to the changes observed in a static tensile test (tensile strength).

TEM structure

TEM examinations aimed at an analysis of the solid solution decomposition during aging of the supersaturated solid solution of alloys from the 6xxx series containing either vanadium or the additions of copper and vanadium.

As-extruded alloy

In the structure of the examined alloys V02, RV01 and RV02 after the extrusion process, the precipitates of fine phases with vanadium were observed. Figure 6 shows the selected as-extruded microstructures of samples of the 6xxx alloy containing copper and the addition of 0.2% V. The precipitates of two types was observed, i.e. rhombohedral precipitates ranging in size from 80 nm to 320 nm and large rod-like shaped precipitates of the size exceeding 700nm. The average size of the precipitates was similar and was about 400nm.

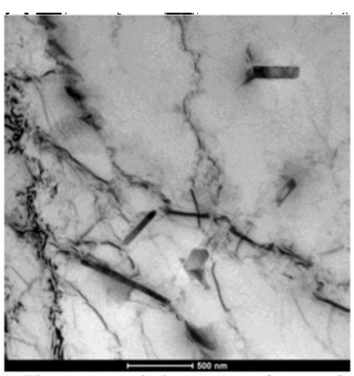


Figure 6. The as-extruded structures in samples RV02

Solution-heat treated alloy

The structure of solution-heat treated samples (Fig. 7) showed no evidence of the presence of fine-dispersed hardening phases Mg_2Si and Al_2Cu. Large phases along the grain boundaries, which would testify the low cooling rate after solution heat treatment, were not traced, either. On the other hand, the sample without the addition of vanadium contained large iron precipitates (above 500nm), which mainly included elements such as Al, Fe, Si, occasionally Mg, Ni, Cr. In samples that contained either vanadium, or the addition of vanadium and copper, small precipitates (in the range of 50nm to 500nm) appeared (Fig. 7).

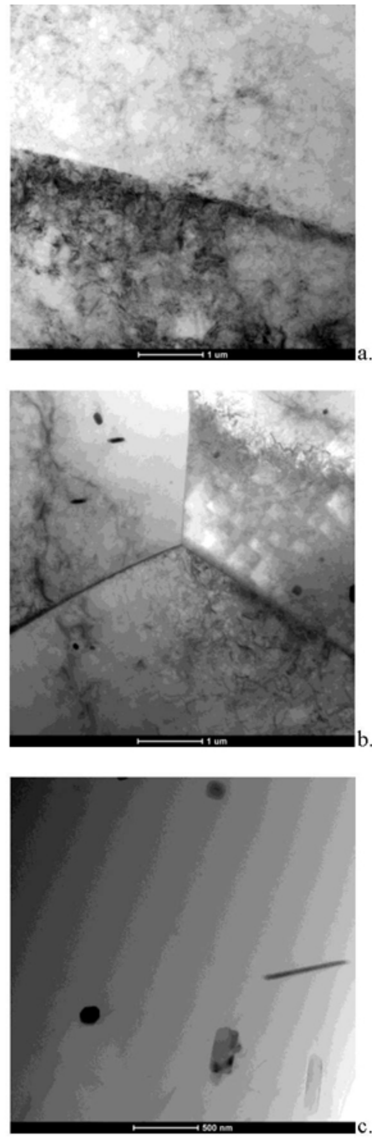


Figure 7. The solution heat-treated structures in samples: V0 (a), V02 (b) and RV02 (c)

Aged alloy

Aging of a 6xxx alloy with the addition of vanadium and copper resulted in the precipitation of fine-dispersed, hardening phases of Mg_2Si (V0, V02) and Al_2Cu+ Mg_2Si (RV01, RV02) (Fig 8).

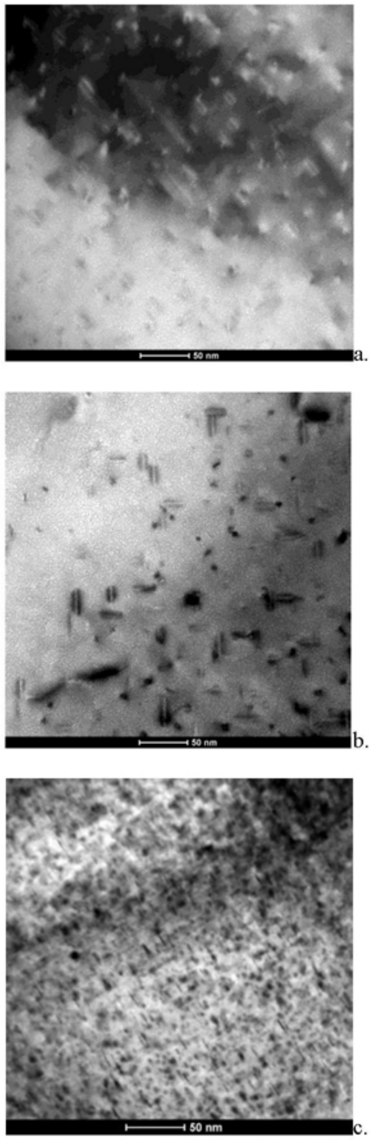


Figure 8. The precipitation of fine-dispersed, hardening phases of Mg_2Si in V0 (a), V02(b) and Al_2Cu+ Mg_2Si in RV02 (c) after 4 hours of aging.

After 4 hours of aging, the structure and chemical composition of the fine precipitates with vanadium did not change compared to the same samples examined after the solution heat treatment. Their chemical composition was strictly related with their shape.

The precipitates of rhombohedral were of a complex composition. The base elements were Al, Fe, Si, V, and additionaly Mg, Cu, Cr, Ni, Mn (Fig. 9a).

Precipitates in the form of rods were composed of the phases of two types, i.e. AlVMg (Fig. 9b) and AlFeVSi(Cu) (Fig. 9c).

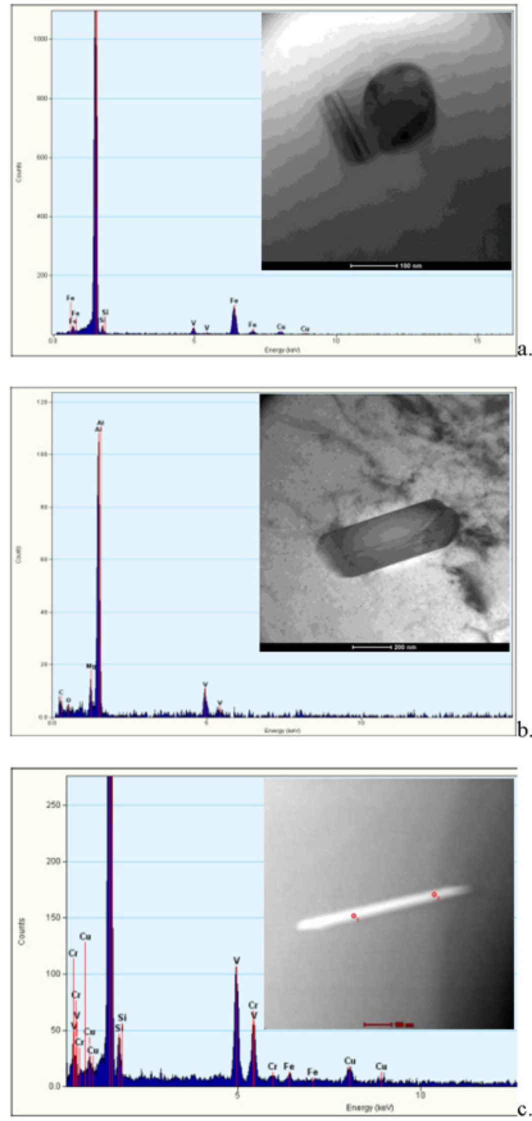
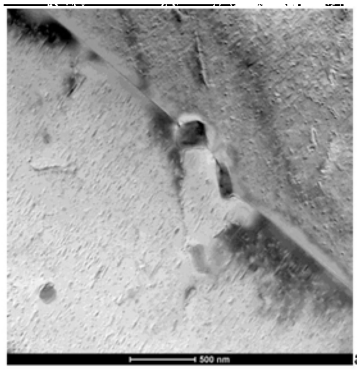


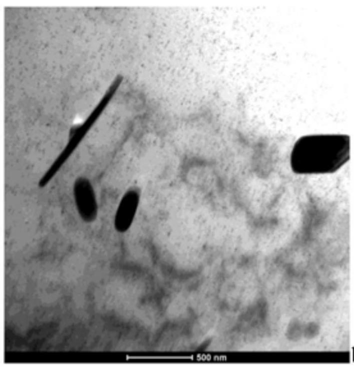
Figure 9. The different precipitates with vanadium after 4 hours of aging

The RV02 sample was reported to have a larger amount of fine phases in the size range from 50 to 500 nm as compared to the other two examined samples - V02 and RV01.

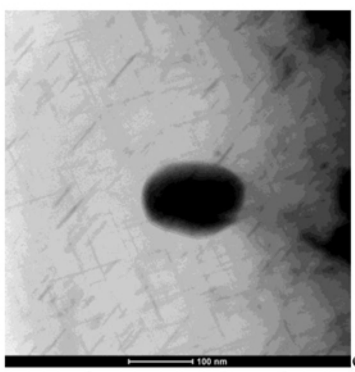
Figure 10 shows examples of the TEM images of structures obtained in the V02, RV01, RV02 samples after 64 hours of aging. Fine-dispersed hardening phases Al_2Cu and Mg_2Si were enlarged which is related to the changes in mechanical properties.



a.



b.



c.

Figure 10. The structures after 64 hours of aging in samples: V02 (a), RV01 (b) and RV02 (c)

Samples containing, besides vanadium, also copper were characterised by a larger number of the fine precipitates (Fig. 11). Fine precipitates are of rhombohedral or rod-like shapes, but also rounded configurations appear in the microstructure. They differ in chemical composition, and a strict relationship between this composition and the sample shape exists.

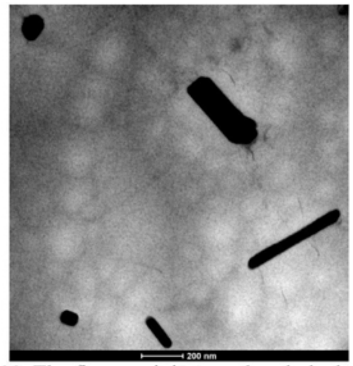


Figure 11. The fine precipitates - rhombohedral, rod, and rounded- like shapes in RV02

Conclusions

Based on the results obtained in the present studies, it has been concluded that:

1. Heat treatment alloys 6xxx series with vanadium and vanadium-copper, comprising solutioning at 530°C/2h and aging at 175°C causes a significant increase in mechanical properties.
2. Aging curves (hardness and strength) for the tested 6xxx series alloys with an addition of vanadium and copper + vanadium, solution heat treated at 530°C/2h and aged at 175°C, showed the optimum aging time for the T6, T61, T64 and T7 states.
3. Increasing vanadium content in the 6xxx series alloys slightly reduces the mechanical properties, while the addition of vanadium and copper significantly improves these properties. The addition of 0.2 wt% vanadium significantly increases the elongation of the examined alloys.
4. Samples with either V or V + Cu contain numerous fine precipitates in the size range of 50 to 500nm. Vanadium addition influenced on changes in the shape of the precipitates, making fine rounded or elongated (oval-shaped) precipitates appear besides the commonly observed rhombohedral and rod-shaped forms.

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