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Effect of Solution Annealing Temperature on Structure and Mechanical Properties of EN AW 2024 Aluminium Alloy

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Abstract

The effect of solution annealing temperature on the change of microstructural and mechanical properties of EN AW 2024 aluminium alloy was investigated using a metallographic analysis, Vickers hardness measurement and tensile test. An intensive growth of solid solution grains was the result of the increase of solution annealing temperature by the finely dispersed particles dissolved during applied annealing process. The role of these finely dispersed particles was to inhibit the recrystallization process and grain growth of solid solution matrix through its pinning effect on the migrated solid solution grain boundaries. Observed changes of the microstructure involved the strength decline and plasticity enhancement of analysed alloy quenched after solution annealing as well as the hardness decrease of naturally aged alloy.

Key words: EN AW 2024 aluminium alloy, solution annealing temperature, mechanical properties, hardness, microstructure, grain growth, intermetallic particles

Introduction

The aluminium alloy EN AW 2024 is widely used AlCuMg alloy in aircraft structures, rivet hardware, truck wheels, screw machine products, and other miscellaneous structural applications on the score of its excellent strength vs. density ratio, formability and corrosion resistance.[1, 2] Developed in the early times in the aircraft industry, alloys of this type have been then considered as a substitute of steel in the transportation industry. Several technical compositions are standardized and new alloys of this type are developed.[3]

Alloy EN AW 2024 is precipitation-hardening alloy which is subjected to a solution treatment, quenching, and a natural or artificial ageing treatment in order to obtain the optimum combination of mechanical properties. The mechanism of precipitation-hardening is based on the formation of intermetallic products during ageing treatment after the decomposition of a supersaturated solid solution (αSSS) obtained by solution treatment and quenching. During ageing treatment the two precipitation sequences are mainly responsible for precipitation hardening of this alloy type, namely [3–11] (α_{SSS}) →GP zones →θ´´→θ´ (the metastable Al_2Cu phases) →θ Al_2Cu) and (α_{SSS}) →GPB zones → S´´→S´ (the metastable Al_2CuMg phases) → S (Al_2CuMg). Depending on the alloy composition (Cu content, Cu/Mg ratio) and ageing parameter, different phase with different distribution, and consequently different material properties, can be obtained.

The coarse second intermetallic phase particles present in structure of this alloy type are responsible for the low fracture resistance, because these particles act like the cracks initiators or the preferential cracks paths.[12] The formation of intermetallic particles results from the presence of impurities, e.g. Fe and Si, and excessive content of alloying elements such as Cu, Mg, Mn in this type of aluminium alloys. Therefore, the important requirement is to lower the coarse intermetallic particles volume fraction in this type of alloys and in this manner to improve the fracture toughness and the plasticity of alloys.[12-16] It is then possible to improve the fracture toughness of alloys by dissolution and modification of the soluble intermetallic particles during applied stepped solution treatment.[13]

In this paper, we focus on the experimental investigation of the effect of solution heat treatment condition on the microstructure and mechanical properties of EN AW 2024 aluminium alloy after quenching and after natural ageing.

Materials and Experimental

The investigation has been carried out on the commercial aluminium alloy EN AW 2024. The chemical composition of the analysed alloy is indicated in Table 1. The hot rolled bar with a diameter of 10mm, industrially processed in T4 temper, was used as initial state in the present investigation. The influence of solution annealing temperature on mechanical properties and microstructure of analysed alloy after quenching was especially investigated.

Table 1. Chemical composition of the investigated alloy

Element	Cu	Mg	Mn	Fe	Si	Zn	Al
Content in wt.%	4.2	1.4	0.91	0.20	0.10	0.03	bal.

The experimental samples of analysed alloy were heat treated, with a wide range of solution annealing temperature from 500 – 570°C and holding time 2.5h in vacuum. Subsequently, the hot heat treated samples were cooled by quenching in water. The water-quenched samples were subjected to natural ageing to 300h. The Vickers hardness measurement (load: 98N) and the metallographic investigations of analysed alloy states were realised in the samples cross-sections. The shape and parameters of specimens for tensile test are depicted in Figure 1, were cut from initial state bar in the rolled direction. Tensile tests were carried out at room temperature using a constant strain rate 2.5 x 10-4 s-1. Microstructures of analysed samples were prepared using common metallographic methods and observed using an optical microscope (OM) and scanning electron microscope (SEM) on etched (Kroll´s etchant) samples. EDX analysis was used to determine the nature of intermetallic particles.

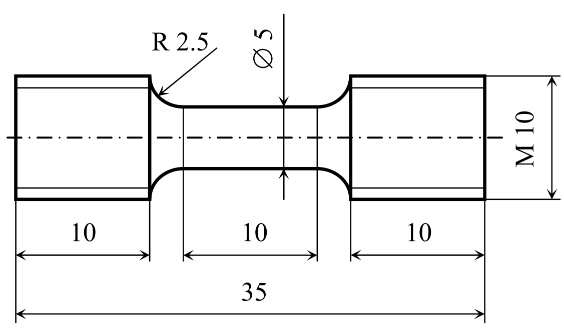

Figure 1. The shape and parameters of specimen for the tensile test

Results and Discussion

The microstructure of the analysed alloy initial state is shown in Figure 2. The dark-gray regions of polyedric grains (grain size: 3.1µm), un-equiaxed grains and a high quantity of fine dispersive particles (particle size: < 1µm) with uniform distribution in matrix were observed in structure of the initial state. Except of these fine particles, coarse irregular intermetallic particles (average size: 7µm) are also present in this structure Figure 3, marked - A. According to EDX analysis Figure 4, these observed particles are multicomponent phases with a high content of Al, Fe, Mn and Cu and enriched by Si. This type of particles is commonly present in commercial aluminium alloys [12 - 15]. In the structure of initial state, undissolved uniphase particles on base Al_2CuMg were also observed (Figure 3., marked-B). EDX analysis of this particle indicated typical composition for Al_2CuMg phase, Figure 5.

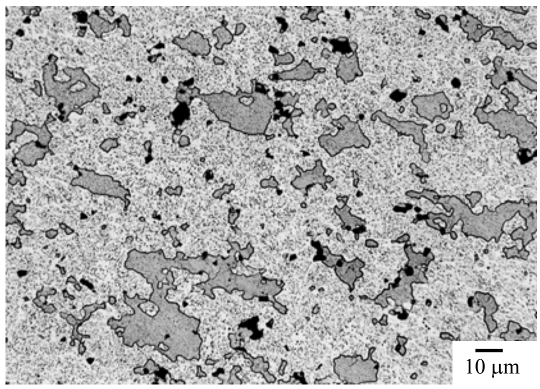

Figure 2. Microstructure of the initial state of analysed EN AW 2024 alloy; etched; OM

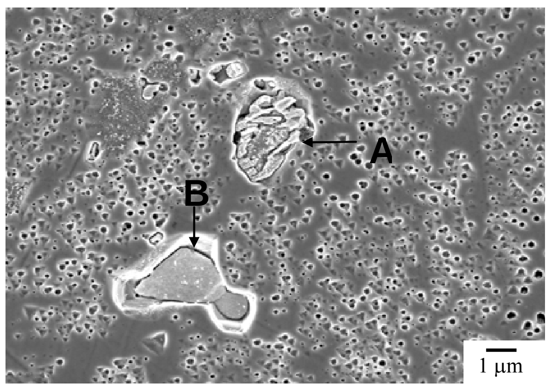

Figure 3. Intermetallic particles in the structure of initial state of analysed alloy; etched; SEM

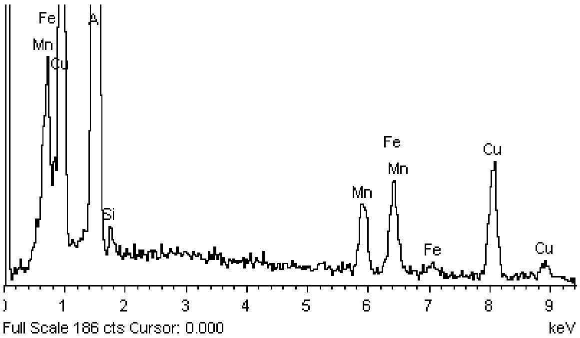

Figure 4. EDX spectrum of intermetallic particle (marked - A) documented on Figure 3

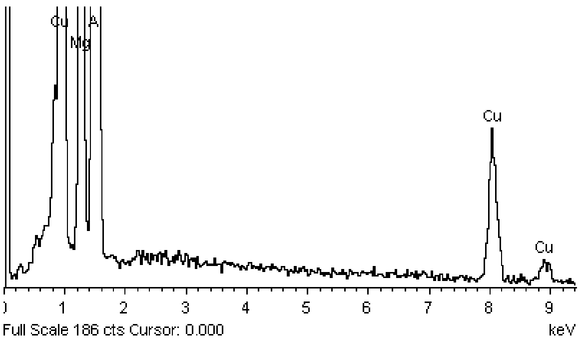

Figure 5. EDX spectrum of intermetallic particle (marked - B) documented on Figure 3

The microstructure of investigated alloy, which was subjected to solution annealing at temperatures of 500°C and 520°C and subsequently quenched, is given in Figure 6a. The structure character of this quenched state and initial state is similar. The presence of recrystallized grains without fine dispersive intermetallic particles and un-recrystallized regions with high quantity of dispersive particles is typical for the structure of these quenched states. In commercial age-hardened aluminium alloys Mn is usually added to form dispersive particles, which inhibit grain growth of matrix and recrystallization (13 and 16). In our work, the annealing at 500 or 520°C evoked the slight grain growth Figure 7. in recrystallized areas in comparison with the grain size of initial state structure. The higher quantity reduction of the fine dispersive particles in some regions of the structure occurred at a higher temperature of annealing (540°C), which is obvious in the structure on Figure 6b. The fine dispersive particles were partially dissolved and coagulated during applied annealing process. The result was the growth of solid solution grains in the regions of structure without dispersive particles Figures 6 and 7.

The solution annealing at temperatures over 540°C led to a complete dissolution and/or coagulation of these fine dispersive particles. Since, the solid solution grains started to grow intensively throughout the whole volume of alloy (Figures 6c and 7). A modification of coarse intermetallic particles parameters also occurred during applied solution heat treatment at higher temperatures. The multiple three-phase particles of eutectic type observed in the initial state (Figure 3) were changed during annealing process and became more regular (Figure 6c). Its volume fraction and size was increased on the score of its coagulation. The phase composition of these particles was also changed. After solution annealing at 550 and 560°C, only two types of uniphase intermetallic particles were observed. The similar change of intermetallic particles character was also present in works (13 and 17).

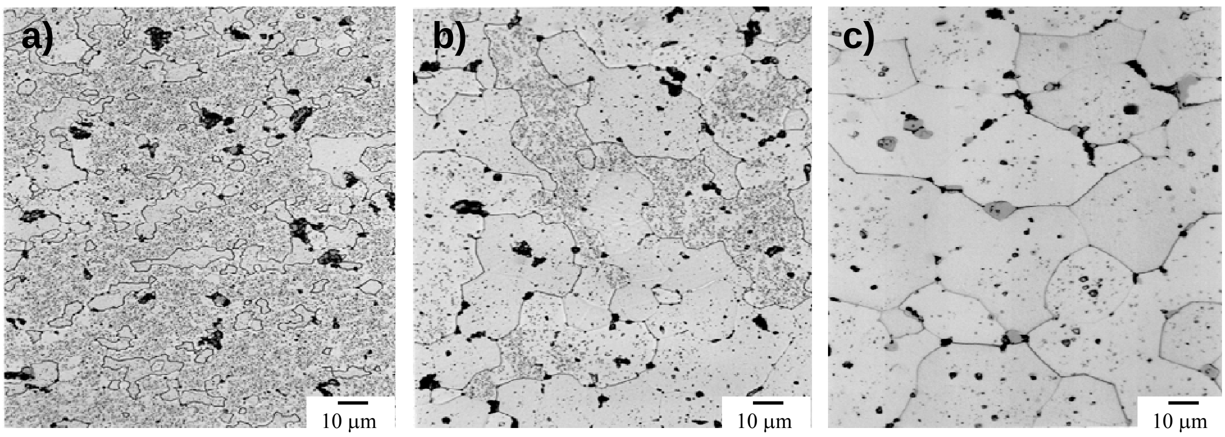

Figure 6. Microstructure of analysed quenched states after solution annealing at various temperatures; etched ; OM ; the solution annealing temperature: **a)** 520°C; **b)** 540°C; **c)** 560°C

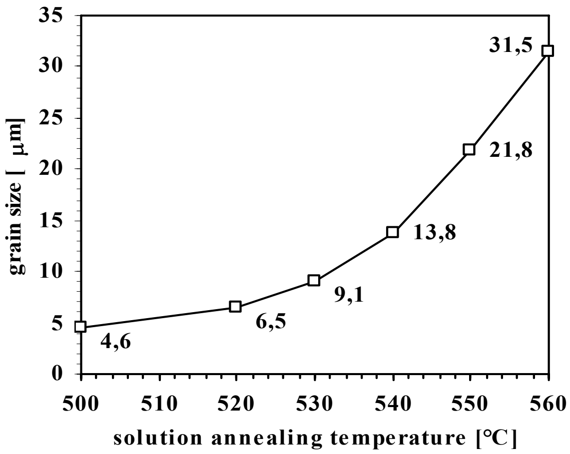

Figure 7. Influence of the solution annealing temperature on the grain size of analysed alloy

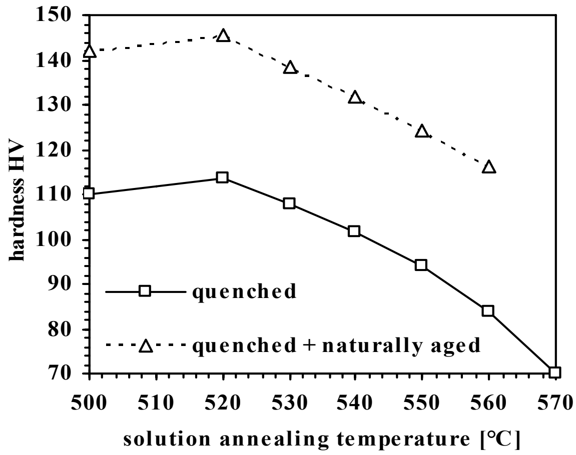

Figure 8. Influence of the solution annealing temperature on hardness of analysed alloy

The results of Vickers hardness measurements realized for quenched states of analysed alloy are depicted in Figure 8. After application of the solution heat treatment and quenching, the hardness of analysed alloy was markedly decreased to the range (70.2 - 113.6HV) in comparison with hardness of initial state (150HV). This trend was confirmed by the tensile test realised for initial state and quenched states after annealing at various temperatures. Results of the tensile test are present in Table 2 and depicted by tensile stress – strain curves in Figure 9. The decrease in strength values (UTS and especially YS) for quenched states indicated softening of initial state of analysed alloy during applied solution heat treatment. The softening was result of dissolution of the strengthening GP, GPB zones, and eventually undissolved Al_2Cu or Al_2CuMg phases into solid solution during annealing process. The increase of annealing temperature from 500°C to 520°C caused the increase in hardness value even though grains softly grew during annealing at 520°C (Figure 7). This was the result of substitute solid solution strengthening through the dissolution of more undissolved Al_2CuMg or Al_2Cu particles. Increase of the annealing temperature over 520°C led to successive decline of hardness and strength for quenched states. However, the plasticity of quenched alloy after application of annealing at higher temperatures (especially at 560°C) was enhanced. An alloy melting at grain boundaries and particle-matrix interfaces, which occurred during the solution annealing at 570°C, resulted in the minimum hardness value (70.2HV) of alloy after quenching.

Table 2. The values of mechanical properties for the initial state of analysed EN AW 2024 aluminium alloy and for the quenched state from various solution annealing temperatures (520, 540, and 560°C)

state; annealing temperature	Initial	520°C	540°C	560°C
Ultimate tensile strength (UTS)	571 MPa	510 MPa	462 MPa	391 MPa
0.2 % Yield stress (YS)	464 MPa	259 MPa	237 MPa	209 MPa
Elongation to failure (El.)	14.5 %	16.1 %	19.3 %	25.8 %

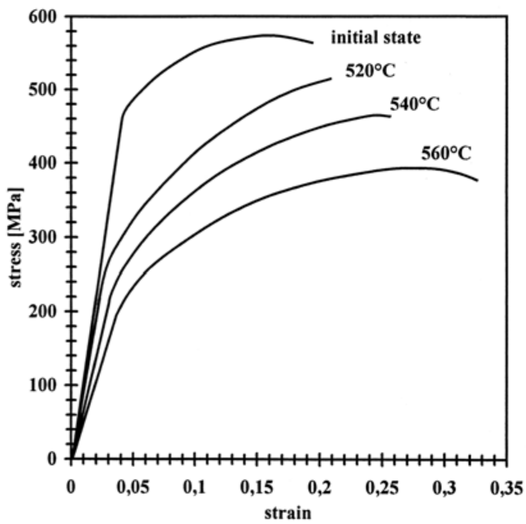

Figure 9. Tensile stress – strain curves for the initial state of analysed alloy and for quenched state after annealing at various temperatures (520, 540, and 560°C)

The decreases in hardness values and strength characteristics such as yield and ultimate tensile strengths, decline of quenched states after the application of solution heat treatment, corresponds to the observed grain growth of solid solution, which was generated by increasing the annealing temperature in the range 520 - 560°C. The successive dissolution and coagulation of the fine dispersive particles, which had strengthened effect (4) on properties of initial state of naturally aged alloy, contributed also to the softening of analysed alloy during applied solution heat treatment at higher temperatures.

The hardness values change of naturally aged states is also given in the graph on Figure 8. The tendency of measured hardness values change of naturally aged alloy states copies the hardness change tendency of quenched states evoked by change of the solution heat treatment temperature. Increase in the hardness values during applied natural ageing process is nearly equal (~ 31.5HV) for all annealing temperatures, because quantity of Cu and Mg atoms dissolved in solid solution is similar for all annealing temperatures. Therefore, the hardening of analysed alloy throughout applied natural ageing is equal for all temperatures of solution heat treatment.

Conclusion

The increase of solution annealing temperature generated the dissolution and coagulation of the fine dispersive intermetallic particles and character modification of coarse multi-phase intermetallic particles present in the initial state (hot rolled and natural ageing) of analysed EN AW 2024 aluminium alloy.

The dissolution and coagulation of the fine dispersive particles were to inhibit the recrystallization process and grain growth, caused the intensive grain growth during solution annealing at higher temperatures (>540°C).

Observed changes of the microstructure involved the decline of strength characteristics and plasticity enhancement of analysed alloy quenched after solution annealing as well as the hardness decrease of analysed alloy after applied natural ageing.

Acknowledgement

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