MINING AND METALLURGY
INSTITUTE BOR

and

TEHNICAL FACULTY BOR,
UNIVERSITY OF BELGRADE

55th International October Conference on Mining and Metallurgy

PROCEEDINGS

Editor:
Ana Kostov

15 – 17 October 2024
Hotel "Đerdap" Kladovo, Serbia

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IMPACT OF AGING PARAMETERS ON DIFFERENT PROPERTIES OF THE EN AW-6082 ALUMINUM ALLOY

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Abstract

This research investigates how the thermal, mechanical, and structural properties of the EN AW-6082 aluminum alloy are affected by the aging parameters (temperature and time). To investigate these properties, the thermal diffusivity and hardness were measured, and scanning electron and transmission electron microscopes were used to detect the structural changes. The heat treatments consisted of solutionizing at 550°C for an hour and then quenching in the ice water, followed by aging at two different temperatures (180°C and 200°C) for 1-8 hours. Investigation revealed that the hardness increases gradually with the aging time, reaching a maximum of 124 HV_{10} *after aging at 180°C for six hours. Similarly, the thermal diffusivity increases with both aging time and temperature, peaking after aging at 200°C for five hours. An SEM/EDS analysis shows the presence of finely dispersed precipitates that contain Mg, Si, and Fe. The TEM investigation confirms the existence of nanometer-sized rod-shaped precipitates believed to be the strengthening β'' phase.*

***Keywords**: aging, thermal diffusivity, hardness, microstructure, EN AW-6082*

1. INTRODUCTION

The Al-Mg-Si alloy system includes many different alloys; among those is the EN AW-6082 aluminum alloy, which has an attracted researcher attention due to its technological significance and notable increase in hardness due to the precipitation hardening [1–3]. In addition to the mechanical properties, the aging (precipitation) can also enhance properties such as the electrical conductivity, thermal diffusivity, and thermal conductivity [4]. In order to cause precipitation, the alloys must first be solutionized, quenched, and then aged. During the aging process in this alloy, the precipitates appear according to the already-known precipitation sequence, which can be represented as α_{ssss} (supersaturated solid solution) → Mg: Si clusters → GP zones (pre-β") → β″ → β′ → β (Mg_2Si) [5–9]. The precipitation of various metastable phases, primarily the β'' precipitates, is responsible for alteration in mechanical, thermal, and structural properties [7]. The formed precipitates create a significant lattice distortion due to their incoherency with the matrix, leading to a reduction in dislocation movement and an increase in the alloy hardness [9]. The desired hardening of alloys from this system is usually achieved by their aging for an extended period at temperatures below 200°C. Many researchers have investigated the effect of aging time on mechanical, structural, and other properties, as evidenced in various studies [1,2,5,7,9-11]. The EN

AW-6082 aluminum alloy is an excellent option for manufacturing the thermal components that require a high strength in addition to the satisfactory thermal properties. Consequently, several researchers have investigated the impact of precipitation on thermal properties of the Al-Mg-Si alloys [4, 6, 12-15]. It can be inferred from the analyzed literature that the thermal and mechanical properties are significantly affected by the aging parameters, which emphasizes the importance of continuing research in this area. Therefore, the focus was on studying the aging parameters, including one ordinary aging temperature (180°C) and another temperature that was higher than the ordinary one (200°C). The thermal diffusivity, hardness, and microstructure after aging for one to eight hours were investigated at both investigated temperatures.

2. EXPERIMENTAL

An investigation was conducted on an EN AW-6082 aluminum alloy. The alloy was received in the form of extruded rectangular bars in a peak-aged condition. All samples underwent annealing at 550°C for 6 hours in the electric resistance furnace Heraeus K-1150/2, and were cooled in air to remove the as-received condition. Samples were heated again at 550°C for one hour and quenched in ice water to obtain a supersaturated solid solution (α_{ssss}). Isothermal aging was performed at 180°C and 200°C for 1–8 hours. The properties of the aged samples were compared to those of the as-quenched sample (annotated as a quenched state in the presented figure) to highlight the impact of aging. After each step in the heat treatment process, samples underwent different characterizations. The hardness of samples was measured according to the ASTM E384 standard [16] on the VEB Leipzig Vickers hardness tester with a 10 kg load and 15 s dwelling time. The thermal diffusivity of samples was determined using the xenon flash method on the TA Instruments DXF 500 thermal conductivity meter. Four different samples were selected for the thermal diffusivity measurements, based on their hardness values. These samples included the underaged samples (aged for 1 hour at 180°C and 200°C) and peak-aged samples (aged for 5 or 6 hours at 180°C and 200°C). The hardness measurements were used to determine if samples were underaged or peak-aged. The investigation was conducted on these samples at four different temperatures (25°C, 75°C, 150°C, and 250°C). To conduct the metallographic investigation of samples, the TESCAN Vega 3 LMU scanning electron microscope equipped with an EDS X-act detector by the Oxford Instruments was used. At the nano level, transmission electron microscopy was used to analyze the microstructure. Sample with the highest hardness (aged at 180°C for 6 hours) was chosen for this analysis. In order to obtain the transparent TEM foils, a "Gatan PIPS 691" was used for sample preparation. The TEM analysis was carried out on a "Jeol JEM 2010F" transmission electron microscope.

3. RESULTS AND DISCUSSION

The effects of isothermal aging on the hardness values of EN AW-6082 are presented in Figure 1. As the aging time increases, the hardness of samples gradually increases until it reaches its maximum value and then decreases. The maximum hardness value was achieved after aging for 6 hours at 180°C, with a value of 124 HV_{10}, which is 74.6% higher than the hardness value of quenched sample (71 HV_{10}). It is believed that the pre-β" metastable phase precipitates during the first four hours of aging due to the creation of numerous vacancies after quenching, which promotes a nucleation of the pre-β" phase. During aging, the Mg and Si atoms diffuse from the solid solution and migrate towards the pre-β" phase, exchanging places with the Al atoms. The existing precipitates transform, and the overall amount of precipitates increases leading to a gradual loss of coherence with the Al lattice. As the aging continues, the exchange of alloying element atoms with Al atoms increases, and the phase transformations continue according to the precipitation sequence [7]. Consequentially, confirmed by several researchers [1-3,5,7,10,11,17]. According to Marioara et al. [2], the incoherency with the lattice increases during the precipitation of the β" phase, even though the precipitate density is low, resulting in the maximum hardness. Precipitates of the β" phase grow and coagulate after 6-8 hours of aging, leading to a decline in hardness values. An additional analysis of graphs, given in Figure 1, shows that the higher aging temperatures lead to a faster reaching the maximum hardness values. However, the highest hardness values, achieved after aging at higher temperatures, are inferior to those obtained after aging at lower temperatures. During the initial one hour of aging, the hardness values are greater when isothermally aged at 200°C versus 180°C. This can be explained by the fact that a diffusion rate increases with increasing aging temperature, causing a faster precipitation of the pre-β’’ phase and loss of coherency. Nevertheless, achieving a genuinely peak-aged state requires the use of lower aging temperature with longer aging times. Tables 1 and 2 provide an information on the thermal diffusivity of aged samples, which was investigated at four different temperatures. Two distinct stages in the precipitation process are represented by the selected temperatures.

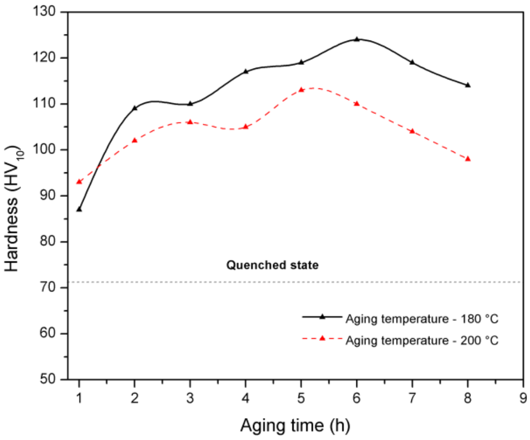


Figure 1. *Change in hardness values of the EN AW-6082 alloy as a function of aging time at two different aging temperatures*

Table 1. *Change in thermal diffusivity after aging at 180°C for different times at different temperatures*

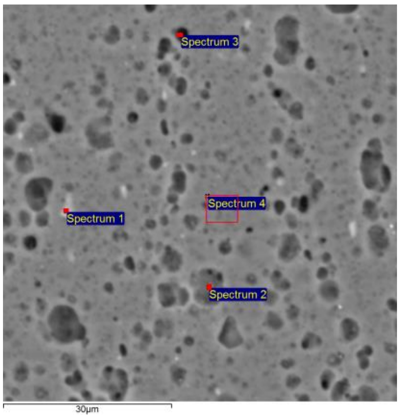
Temperature (°C)	**Thermal diffusivity (mm²/s)**	
	After aging at 180°C for 1 hour	**After aging at 180°C for 6 hours**
25	70.49	76.21
75	70.84	76.17
150	70.88	75.19
250	75.23	74.85

Table 2. *Change in thermal diffusivity after aging at 200°C for different times at different temperatures*

Temperature (°C)	**Thermal diffusivity (mm^2/s)**	
	After aging at 200°C for 1 hour	**After aging at 200°C for 5 hours**
25	76.68	79.66
75	75.85	78.46
150	75.85	77.27
250	78.66	75.55

** Thermal diffusivity of the quenched sample = 73 mm^2/s*

Samples that have undergone aging for one hour represent the underaged samples, while samples aged for five or six hours correspond to the peak aged state, as shown in the hardness graph, Figure 1. The highest thermal diffusivity value was obtained after aging at 200°C for 5 hours, which was 9.12% higher in comparison to the quenched sample. If aged for 1 hour at 180°C, the thermal diffusivity values are lower than those of quenched sample. During this aging process, the pre-β'' phase (GP-zones) is formed, which scatters electrons and leads to a decrease in thermal diffusivity. As the aging time or aging temperature increases (4-5 hours or 200°C, respectively), the number of precipitates increases due to the reduction of alloying elements in the solid solution, leading to an increase in thermal diffusivity [4, 6]. With the precipitation of the β'' phase, the saturation of solid solution is lowest, resulting in the highest values of thermal diffusivity. The results presented in Tables 1 and 2 indicate that diffusion is accelerated at higher aging temperatures, leading to the intensified precipitation and faster reduction of alloying elements in the solid solution, which, in turn, increases the thermal diffusivity. As the measurement temperature (represented by the rows in tables) is increased, the thermal diffusivity decreases due to the thermal vibrations in a lattice. The peak-aged samples confirmed this phenomenon. On the other hand, the underaged samples did not show this behavior. Instead, an abrupt increase in the thermal diffusivity values can be observed at 250°C, which can be attributed to the additional aging. Reheating underaged samples at higher temperatures, at which the precipitation takes place, according to the precipitation sequence, can result in the additional aging. This causes a new amount of precipitates to form, leading to the reduction of alloying elements in the solid solution and facilitating the flow of electrons, resulting in an increase in the thermal diffusivity. The additional analysis was carried out using a SEM-EDS and transmission electron microscope on samples peak-aged at 180°C and 200°C. Figure 2 shows the SEM-EDS analysis, while Figure 3 represents the TEM/SAED analysis. Analysis of Figure 2 shows that the microstructure of the peak aged sample is covered with the finely distributed precipitates, assumed to be the metastable β'' phase, which is shown by the spectrum 4. The spectra 2 and 3 show the somewhat larger particles containing Mg, Si, and Mn. Also, an AlFeSi phase appears in the investigated sample, represented by the spectrum 1 in Fig. 2. The TEM/SAED analysis (Figure 3) shows the precipitation in the sample peak-aged at 180°C for six hours. The SAED (selected area of electron diffraction) image shows the orientation of precipitates in the crystal lattice.



Spec	Mg	Al	Si	Mn	Fe
1		87.66	5.53	2.23	4.59
2	0.54	97.06	2.24	0.16	
3	0.45	98.23	1.31		
4	0.76	97	2.11	0.14	
**values are given in atomic percent*					

Figure 2. *SEM-EDS analysis of the sample peak aged at 200°C for 4 hours*

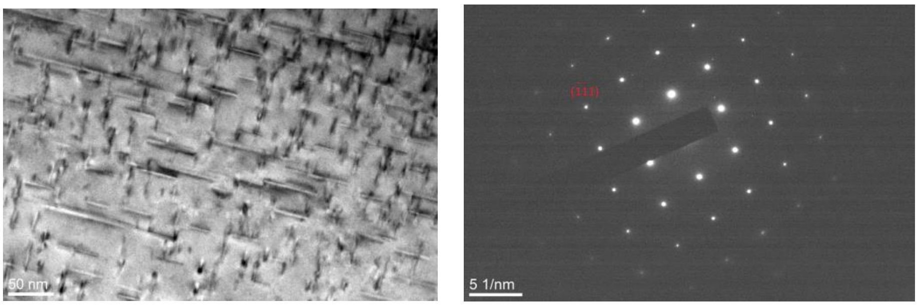


Figure 3. *TEM-SAED analysis of sample peak aged at 180°C for 6 hours*

A TEM micrograph was imaged on the [0 0 1] zone axis of Al in order to visualize the precipitates. It can be concluded from Figure 2 that the small needle-shaped precipitates with a size of several tens of nanometers are visible. The density of precipitates is high, and they are distributed quite evenly throughout the microstructure of investigated sample [2,7,9,10].

4. CONCLUSIONS

A considerable rise in mechanical and thermal properties was observed due to isothermal aging. The most substantial increase in hardness values was detected after aging at 180°C for 6 hours. The precipitation of the metastable β'' phase is assumed to be the reason behind the hardening effect. The thermal diffusivity values peaked after a five-hour aging at 200°C, caused by the highest degree of precipitation from the solid solution. The thermal and mechanical properties were found to be enhanced due to the presence of finely dispersed metastable phases, as confirmed by the microstructural investigation. It is believed that the mainly responsible phase for this enhancement is the β'' phase.

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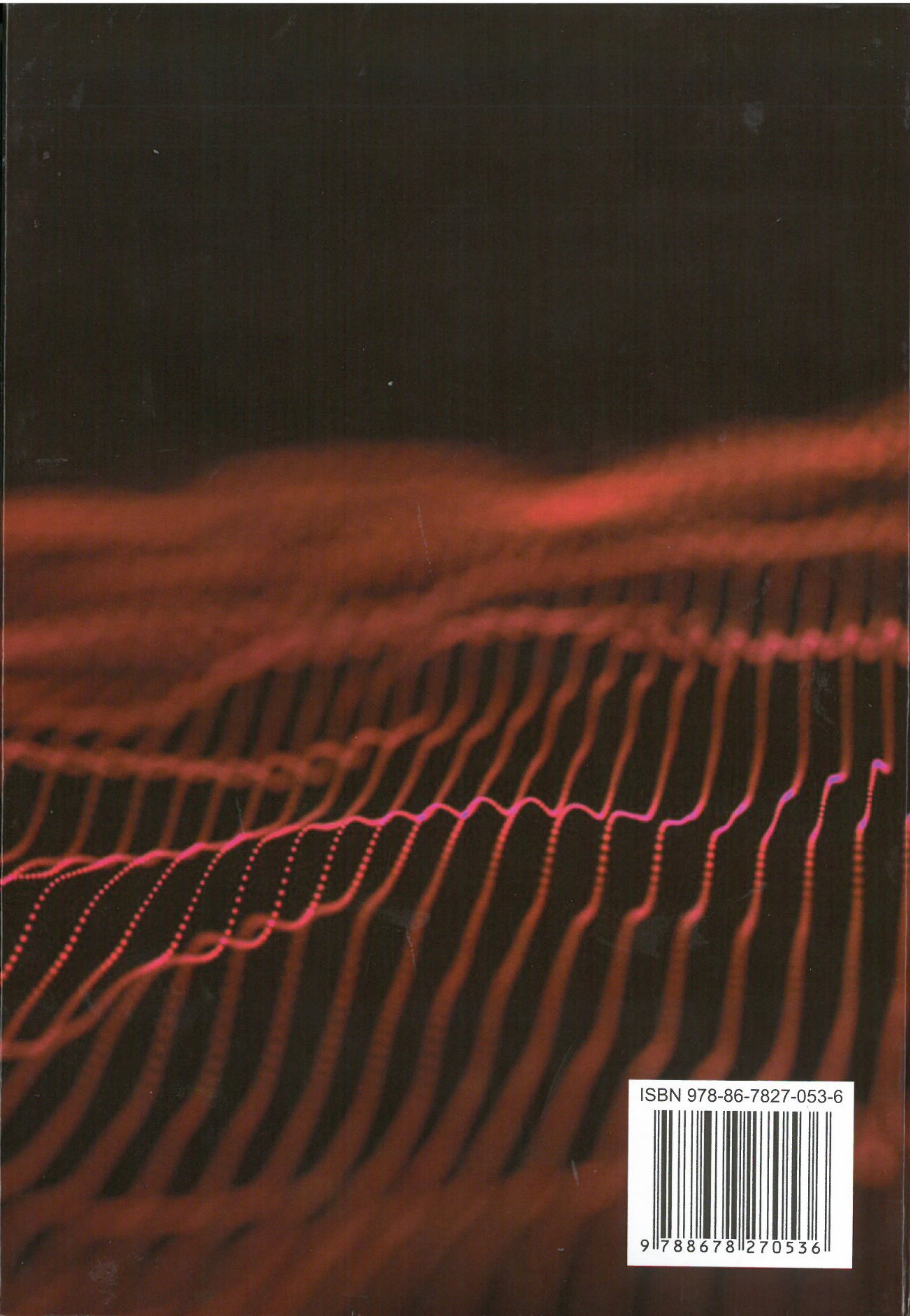

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