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Effect of the Over-ageing Treatment on the Mechanical Properties of AA2024 Aluminum Alloy

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The evolution of the hardness of the over-ageing AA2024 alloy scale was followed by measurements of Vickers hardness. The nanoindentation is adapted to the determination of elastoplastic properties (hardness and Young's modulus) of the matrix and also of coarse intermetallic precipitates. Influence of the artificial over-ageing time to hardness and to mechanical properties as the local scale was investigated.

Keywords: AA2024 aluminum alloy, over-ageing treatment, mechanical properties, hardness, Young's modulus

The aluminum alloys of the 2000 series, AA2024-T351 alloy, are used in the aerospace industry for the wings and fuselage skins of the aircraft, due to the high strength to weight ratio associated with good fracture toughness. A combination of alloying elements, heat treatment and ageing induce the improvement of mechanical properties, as well as good damage tolerance and resistance to fatigue [1-6]. The phenomenon of precipitation hardening and the influence of heat treatment on the mechanical properties of AA2024 alloy have been extensively studied [7, 8]. The microstructure has an important role in corrosion resistance, and some intermetallic particles can be the cause of pitting and intergranular corrosion. The phenomenon of precipitation hardening in aluminum alloys takes place at relatively low temperature and induces the precipitation of intermetallic particles composed of the main alloying elements i.e., copper and magnesium. The fundamental stage of the age-hardening process consists in the acceleration of the decomposition phenomenon of the supersaturated solid solution, resulting in the coarse intermetallic particle precipitation [4, 9, 19], stage where the mechanical properties reaches the maximum values, but at the cost of a low corrosion resistance.

The precipitation of the equilibrium phase, S -Al2CuMg phases and the phases S" and S' is the main responsible for final hardening. Most authors considered that the dislocations serve as the heterogeneous nucleation sites for the S (Al2CuMg) phase in Al–Cu–Mg alloy during artificial ageing [11-19].

The mechanical properties are improved due to hardening precipitation that lead to peak-ageing condition and to the over-ageing condition with increasing ageing. During ageing treatment, the change in mechanical properties function of the treatment time can be plotted as a belle-shape curve, with a maximum value. The evolution of mechanical properties can be described by three successive stages: under-aged temper, aged temper and over-aged temper.

In the figure 1 are represented the evolution of hardness and mechanical strength of the aluminum alloy during ageing treatment [20, 21]. The over-ageing treatment (T7) is supposed to stabilize the microstructure and the mechanical properties to improve the corrosion resistance.

The present work was aimed to investigate effects of over-ageing treatment on the mechanical properties of the AA2024 alloy. The mechanical properties of the AA2024 alloy at the T351 state and over–aged were studied locally (matrix and intermetallic particles) using nanoindentation at very low loads.

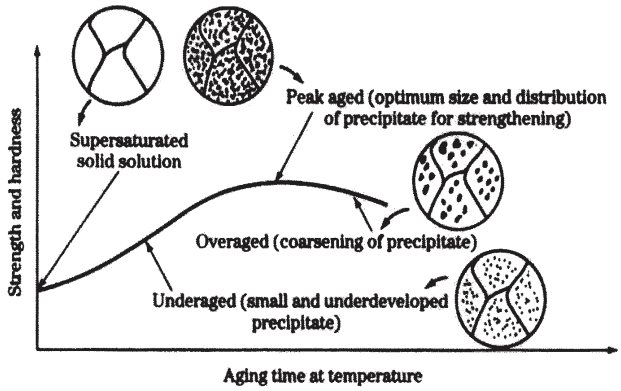

Fig. 1. Evolution of the hardness and mechanical strength as a function de time and temperature treatment[20,21]

Experimental part

The experimental material is AA2024 alloy, and its chemical composition is listed in table 1. All specimens were cut in order to test the longitudinal (L) direction of the material.

Heat treatment

The heat treatment performed on the samples consisted in three successive steps. The sample with size of 1 cm^3, were treated at 495 ± 5 °C in an air circulating furnace for 1 hour, quenched into cold water and immediately aged at three different temperatures: 150, 175 and 190 °C. The treatment duration for each temperature (36 days at 150 °C, 50 h at 175 °C and 24 h at 190 °C) was defined after the macrohardness stabilized. T351 is a heat treatment commonly, used in the aerospace industry, which corresponds to solution treated at 495 ±5°C, water quenched, stretched at 1.5-3%, aged at room temperature.

Preparation of the surface

The method of surface preparation is important for the study of intermetallic particles. The surface preparation consisted of mechanical polishing from SiC paper (grade 600, 1000, 2500, 4000) to a diamond abrasive of 3μm and

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Table 1
CHEMICAL COMPOSITION OF THE STUDIED ALLOY

Chemical element	Al	Cu	Mg	Mn	Fe	Zn	Si	Ti	Cr
wt. %	Base	4.6	1.5	0.6	0.14	0.12	0.08	0.04	0.01

Table 2
HEAT TREATMENTS FOR THE AA2024 ALLOY

Alloy	Designation name for the heat treatment	Solution treatment	Water quenched	Over-ageing treatment
2024	T7-150	495±5°C	water (< 20°C)	150°C, 36 days
	T7-175	495±5°C	water (< 20°C)	175°C, 50 hrs
	T7-190	495±5°C	water (< 20°C)	190°C, 24hrs

1μm. Final polishing, 0.05 μm, is performed using a pure, heavy grade of silicon dioxide (SiO_2). The Vibromet polishing removes the deformation layer remaining after a classical mechanical preparation.

Hardness test and nanoindentation test

The age hardening response of the alloy was monitored by Vickers hardness measurements using a load of 10daN and 30daN. Reported hardness values represent the average of 5 individual measurements.

Instrumented indentation has been widely used for determining the mechanical properties of material, respectively Young's modulus and hardness.The mechanical properties of the matrix of the AA2024 alloy and its coarse intermetallic particles before and after thermal treatment were characterized using an MTS Nanoindenter with a Berkovich indenter tip. The mechanical properties, hardness and elastic modulus were obtained by using nanoindentation test in dynamic mode (Continuous Stiffness Measurement). One of the most used methods for analyzing the mechanical properties is that of Oliver-Pharr [22, 23].

The indentation hardness, H, is found from the eq.1 given as:

$$H = \frac{Pmax}{Ap} \qquad (1)$$

were *Pmax* represented the maximum load and *Ap* is the projected area of the contact at the load between the indenter and the sample. The data are obtained from the load-displacement curve [17,18]. The elastic modulus, Es, is calculated from the eq.2 given as:

$$\frac{1}{E_r} = \frac{1-\nu_s^2}{E_s} + \frac{1-\nu_i^2}{E_i} \qquad (2)$$

where Es and ν_s are the elastic modulus and Poisson's ratio for the test material and Ei and ν_i are the elastic modulus and Poisson's ratio for the indenter.

For the matrix the XP head was used with Berkovich indenter at a maximum depth of 2000 nm. For the coarse intermetallic particles the DCM head was used with Berkovich indenter at a maximum depth of 300 nm. This head allowed obtaining the hardness and Young's modulus at the local scale.

A precise location of the coarse intermetallic particles was needed, so that, the areas of interest (square 2/2mm) were defined. 50 precipitates for each over-ageing conditions were located by optical microscopy.

Results and discussions

Effect of the heat treatment on the Vickers hardness

The artificial ageing leads to an improvement of the mechanical properties. The degree of precipitation hardening is function on the temperature and treatment duration.

The evolution in Vickers hardness, during artificial ageing can be drawn as a curve with a maximum value. Figure 2 presents the hardness variation as a function of the artificial ageing time for the three temperatures. The age hardening curves of AA2024 alloy under all testing conditions have a similar shape, that is, the hardness increases gradually, upto a maximum value and then decreases gradually. So, the maximum hardness (peak hardness) at 150 , 175 and respectively 190 °C is reached after 28 days, 11 h and 7 h of treatment, and a stabilization of the hardness appears after 36 days, 50 h and respectively 24 h. The maximum hardness is in agreement with the peak hardness found in literature [24-26].

The variation of hardness as a function of the artificial ageing time showed two stages that typically appear in the AA2024 alloy.

The first stage of hardening, characterized by an initial rapid hardening, occurs very rapidly, approximately 60 seconds. This stage represents approximately 50-70% of

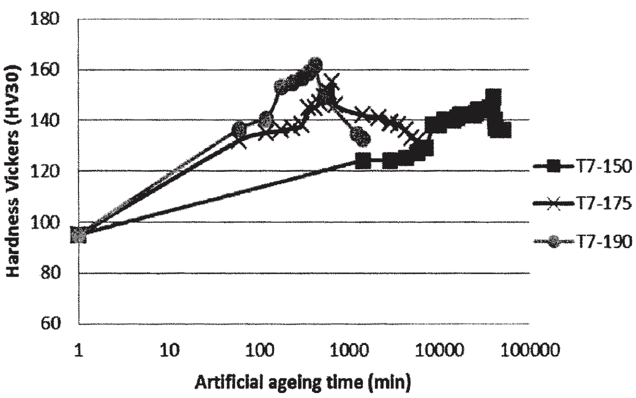

Fig. 2. Hardness as a function on the artificial ageing time at 150, 175 and 190°C

Table 3
HARDNESS FOR THE AA2024-T351 AND AA2024 AGED

Conditions	T-351	T7-150	T7-175	T7-190
Hardness (HV30)	149	136	139	133

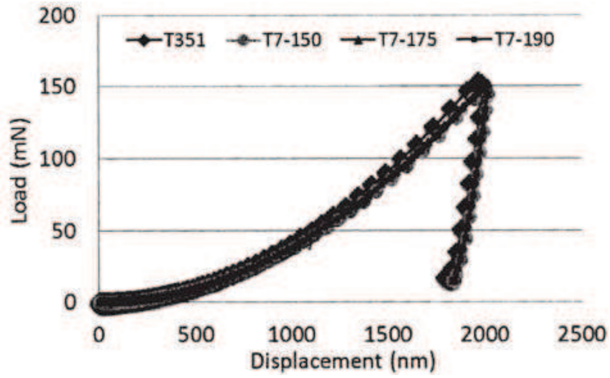

Fig. 3. Load –displacement curve for the AA2024-T351 and AA2024 aged

Table 4
MECHANICAL PROPERTIES OF THE MATRIX

	Young's Modulus (GPa)	Hardness (GPa)	W_P/W_e
T351	84.4 ± 0.1	1.9 ± 0.1	3.7
T7-150	87.0 ± 1.9	1.7 ± 0.1	3.9
T7-175	85.6 ± 0.1	1.8 ± 0.1	3.9
T7-190	84.9 ± 1.1	1.7 ± 0.1	3.9

maximum hardening alloy and corresponds to the formation of Cu-Mg clusters [8, 27-29].

The second stage is characterized by an increase in hardness (peak hardness) and has been attributed to the formation of the Guinier-Preston- Bagaryatsky (GPB) zone, described as short range ordering of one Cu + Mg layer and several Al layers along the {100}Al planes and S–$A_{12}CuMg$ phases [27, 30, 31].

Between these two stages of increase in hardness, there is a "plateau", during which time the hardness does not change for many hours of treatment. The over-ageing treatment (T7) allows stabilizing the microstructure and mechanical properties.

In table 3 are presented the results of the hardness for the AA2024-T351 alloy and for AA2024 aged, for a load de 30 daN. The values of Vickers hardness for the two charges, 10 daN and 30 daN, are similar.

Effect of the heat treatment on the mechanical properties at the local scale

Nanoindentation has been used to determine the mechanical properties of the matrix of the AA2024 alloy for the different ageing conditions, and particularly to determine the mechanical properties of coarse intermetallic particles.

From loading – unloading curves, the mechanical behavior is determined by calculating the ratio of plastic deformation work and the elastic deformation work. This ratio increases slightly after quenching. In figure 3 is presented the load-displacement curve for the matrix of the alloy after T351 treatment and over-aged conditions. The mechanical properties were determined for indentation depths between 150 and 1800 nm.

The Young's modulus and hardness are presented in table 4. The mechanical properties of the materials depend on their microstructure. They depend on the presence of intermetallic precipitates and their surface repartition. These mechanical characteristics were determined for indentation depths between 150 and 1800 nm. The mechanical properties of the matrix (solid solution and hardening precipitates) appear identical for the three treatment conditions chosen. The values of Young's modulus are close to 85 GPa and the values hardness are equal to 1.7 GPa. The hardness values measured by nanoindentation exhibit the same tendency as for the Vickers measurements (136 HV_{30} for T7-150, 139 HV_{30} for T7-175, 133 HV_{30} for T7-190).

In order to determine the mechanical properties of coarse intermetallic particles the nanoindentation tests were performed on 50 precipitates in each aging condition. In figure 4 are presented the load-displacement curves for the matrix AA2024 T7-150 and for the coarse intermetallic precipitates in the same over-ageing condition. We observed that the values of mechanical properties of the precipitates are higher than the corresponding values mechanical properties of the matrix.

The precipitates in which indentations were performed were analyzed by EDS to determine their chemical composition. We determined Young's modulus and hardness values for the S-Al_2CuMg phase particles and the

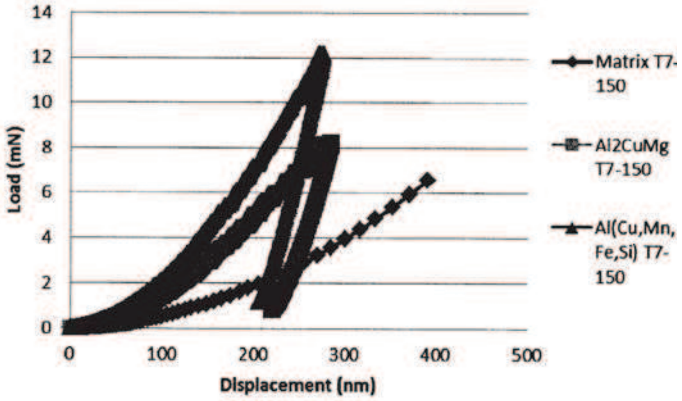

Fig. 4. Load - displacement curve for the matrix, the Al_2CuMg and the Al(Cu,Mn,Si,Fe) particles of the AA2024 alloy

	Al_2CuMg		Al(Cu,Mn,Fe,Si)	
	Young's modulus (GPa)	Hardness (GPa)	Young's modulus (GPa)	Hardness (GPa)
T7-150	131.1 ± 3.9	6.4 ± 0.5	173.7 ± 14.5	9.52 ± 1.1
T7-175	132.7 ±7.8	7.2 ± 0.8	174.7± 17.4	9.5±1.8
T7-190	139.9 ± 3.5	7.5 ± 0.6	179.3 ± 15.6	10.23 ± 1.3

Table 5
MECHANICAL PROPERTIES OF COARSE INTERMETALLIC PARTICLES

Al(Cu,Mn,Fe,Si) particles. The results for each condition were presented in table 5. It can be noted that S-phase particles present Young's modulus and hardness values lower than the Al(Cu,Mn,Fe,Si) particles.

Conclusions

Vickers hardness of the over-aged AA2024 alloy was lower than of the AA2024-T351 alloy (136 HV_{30} for the over-aged AA2024 and 149 HV_{30} for AA2024-T351 alloy). At the same time, the treatment duration has been determined for each temperature (36 days for 150 °C, 50 h for 175 °C and 24 h for 190 °C). For these time durations of the over-aging treatment, the hardness was almost identical (136 HV_{30}, 139 HV_{30} and 133 HV_{30} respectively for over-ageing treatment at 150°C, 175°C and 190°C).

The nanoindentation tests have confirmed the similar hardness and Young's modulus values of the matrix (solid solution and hardening precipitates) for the different over-ageing treatments. The mean values calculated for the different treatment are close to 85 GPa for the Young's modulus and 1.7 GPa for the hardness.

The mechanical properties (E, H) of the intermetallic particles are higher than those of the matrix. The hardness values and Young's modulus values of the Al(Cu,Mn,Fe,Si) phases are higher than those of the S-phase.

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