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Study of the variation in mechanical properties of the Al-Mg-Si alloy with ageing time

Estudo da variação das propriedades mecânicas da liga Al-Mg-Sino tempo de envelhecimento

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ABSTRACT
Aluminum alloys have had more and more industrial applications, therefore, it is necessary to study their processing and chemical compositions in order to understand and improve their mechanical properties. The objective of this work is to analyze the chemical composition of an Al-Mg-Si alloy and the effects that the heat treatments of solubilization and aging at different times have on its mechanical and microstructural characteristics. Tensile and Vickers microhardness tests were performed to obtain the mechanical properties of the factory material, then the material was subjected to solubilization at 530 °C for 40 minutes and aging at 180 °C for 0.5, 1, 2, 4, 6 and 8 hours and the Vickers microhardness of the material for each aging time. Metallographic analyses were performed on the factory material, with 4 and 8 hours of aging. The results of the microhardness were compared, which allowed to plot the aging curve of the material and observe the influence of the aging time on the mechanical properties of the alloy.

Keywords: Aluminum alloy, Precipitation hardening, Solubilization, Aging.

INTRODUCTION

There are several types of aluminum alloys, with numerous possibilities of chemical composition, processing and heat treatments that result in different mechanical properties, which makes the area of research in aluminum alloys a vast and inviting field for new studies.

Aluminum-Magnesium-Silicon type aluminum alloy fits into the 6XXX series and is a

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type of heat-treatable alloy, that is, it can have its mechanical properties improved through heat treatments. In industry, they are widely applied in architectural profiles and automotive components (SANTOS, 2015). According to Santos (2015), magnesium is responsible for increasing mechanical strength, while silicon improves corrosion resistance.

In solubilization treatment, all solute atoms are dissolved to form a single-phase solid solution. Considered an alloy of C0 composition with a combination of α and β phases, solubilization consists of heating the alloy to a temperature T0, within the field of α phases, and waiting until the entire β phase is completely dissolved, so that the alloy is composed of only one phase α of C0 composition. This procedure is then followed by rapid cooling, or quenching, to a T1 temperature, which is usually room temperature (CALLISTER, 2021)

Aging is based on the combination of temperature and time during precipitation treatment, a fundamental part of the process to obtain the desired properties in the alloy.

Specifically for aluminum alloys, Petty (1962) developed correlations that estimate the values for tensile strength strength and yield strength in ton/in² through the measurement of the material's Vickers hardness, displayed by Equations 1 and 2, respectively:

$$LEPetty(ton/in^2) = (0.148 \text{ x } HV) - 1.59$$

$$LRTPetty(ton/in^2) = (0.189 \text{ x } HV) - 1.38$$

Since Petty's equations result in the unit ton/in², it is enough to multiply the result by 15.4448 to obtain the value in MPa.

To estimate the mechanical strengths of the material, Petty's correlations will be used in this work.

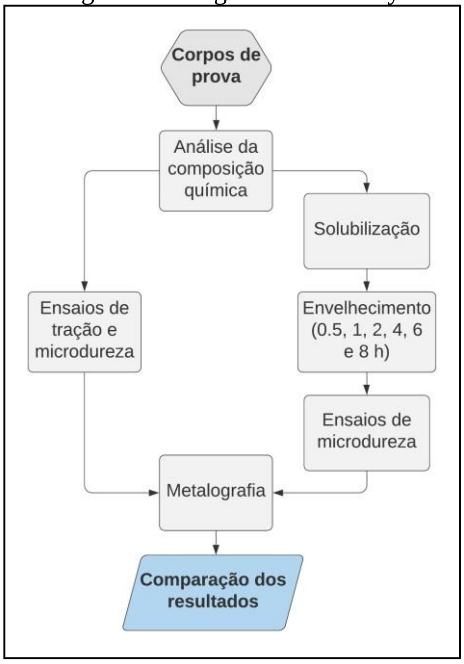
METHODOLOGY

Initially, specimens were obtained from aluminum alloys without heat treatment. A part of the specimens was submitted to chemical composition analysis, tensile tests, microhardness and metallography. The other specimens were heat-treated with solubilization and different artificial aging times, and then they were also subjected to microhardness tests and metallographic analysis.

The results obtained were analyzed for the purpose of comparing the mechanical properties of pre and post heat treatment of the materials.

All processes were carried out at LEME (Laboratory for the Study of Materials and Tests) of the Federal Technological University of Paraná, Cornélio Procópio campus. Figure 1 shows the diagram of the study's activities:

Figure 1 – Diagram of the study.

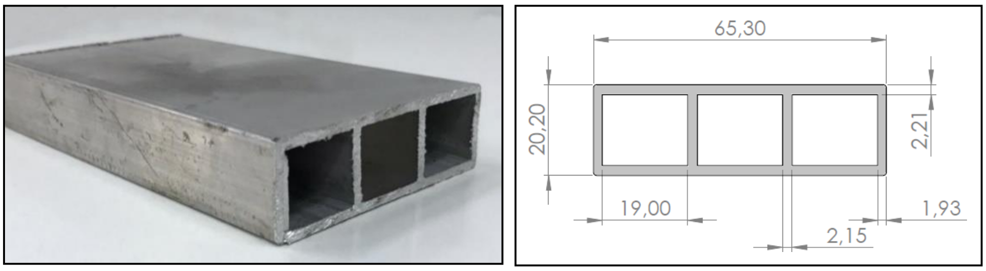


Source: Author (2024).

MATERIALS

The specimens were obtained from two extruded structural profiles of different Al-Mg-Si alloys. These profiles are used for the production of net tanks for fish farming. Figure 2 shows the type of profile and Chart 1 shows the identification of the specimens

Figure 2 – Type of Al-Mg-Si structural profile and dimensions.



Source: Author (2024).

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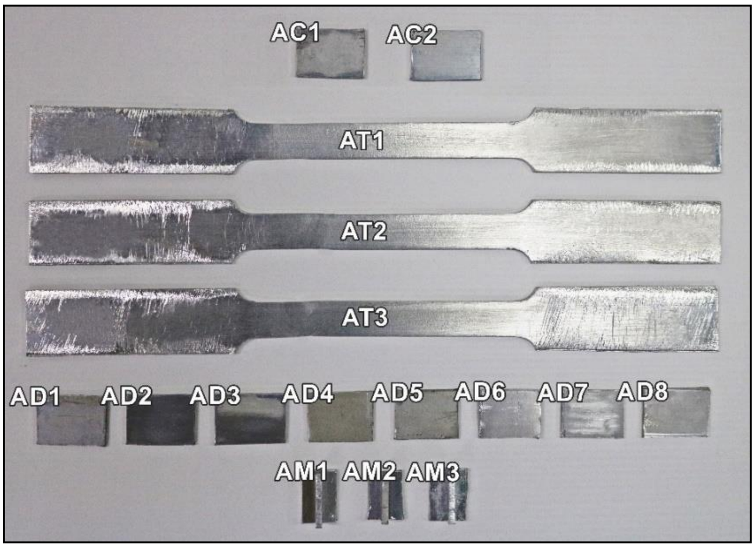
Table 1 – Identification of specimens.

Specimen	Identification	
	League A	League B
Chemical composition	AC1, AC2	BC1, BC2
Traction	AT1, AT2, AT3	BT1, BT2, BT3
Microhardness	AD1, AD2, AD3, AD4, AD5, AD6, AD7, AD8	BD1, BD2, BD3, BD4, BD5, BD6, BD7, BD8
Metallography	AM1, AM2, AM3	BM1, BM2, BM3

Source: Author (2024).

The specimens for Alloy A are shown in Figure 3. The B alloy specimens are similar.

Figure 3 – Specimens used in the study.



Source: Author (2024).

PRE-HEAT TREATMENT TESTS

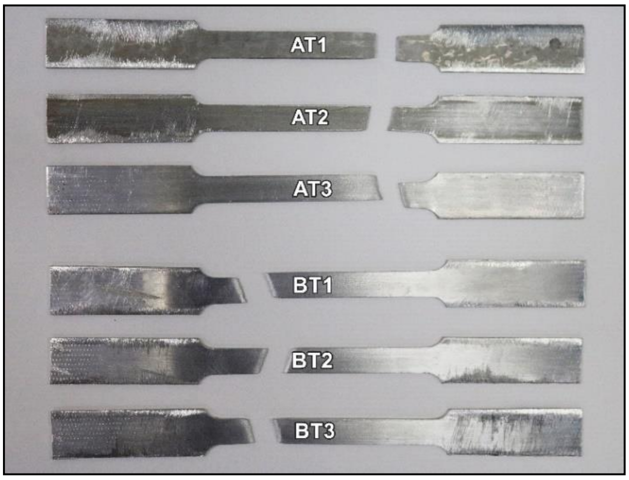
Chemical Composition Analysis

The AC1, AC2, BC1 and BC2 samples of the materials were prepared according to the NBR 15693 standard to identify the chemical composition of the alloy. The analyses were performed at the Bruker Q4 Tasman Spectrometer of the HELM.

Traction

Tensile tests were performed on specimens AT1, AT2, AT3, BT1, BT2 and BT3 at the HELM, using the WDW-100E universal testing machine. Figure 4 shows the test specimens:

Figure 4 – Test specimens.



Source: Author (2024).

Microdureza Vickers

The AD1 and BD1 specimens were prepared in accordance with the NBR ISO 6507-1 standard and tested for Vickers microhardness on the Panatec HV-1000B benchtop micro durometer of the HELM. The load applied in the tests was 0.2 kgf for 10 seconds, using the standard Vickers indenter: diamond pyramidal with 136° between opposite faces. A total of 10 microhardness measurements were obtained for each specimen.

Metallography

The surfaces to be observed from samples AM1 and BM1 were sanded and polished according to the NBR 13284 standard and chemically attacked. Observation and image capture were performed using the Olympus BX53M optical microscope at the HELM.

HEAT TREATMENTS

Solubilization

The specimens AD2-AD8, BD2-BD8, AM2, AM3, BM2 and BM3 were solubilized for 40 minutes at a temperature of 530° C. These parameters were defined based on the NBR 12315 standard, considering aluminum alloys of the 6000 series and the thickness of the material. The solubilization treatment was carried out in the Sanchis Novus N1100 industrial furnace of LEME. After the solubilization time, the specimens were removed from the furnace and immediately submerged in cold water (6° C) for sudden cooling.

Artificial aging

After solubilization, the specimens of the anterior section (with the exception of AD2 and BD2) were subjected to artificial aging. Table 2 shows the aging time designated for the sample:

Table 2 – Aging time for specimens.

Specimen	Aging time (h)
AD3, BD3	0,5
AD4, BD4	1
AD5, BD5	2
Id6, Bud6, Um2, Bomb2	4
AD7, BD7	6
Id8, Bud8, Umm3, Bomb3	8

Source: Author (2024).

The temperature set for aging was 180° C, also based on the NBR 12315 standard for 6000 series alloys. The times ranged from 0.5 to 8 hours to obtain data for the plotting of the aging curves of the materials. After each designated time had been reached, the specimens were removed from the furnace and immediately cooled in water at room temperature.

POST-HEAT TREATMENT TESTS

To evaluate the effects of heat treatments on the specimens, Vickers microhardness tests and metallography analysis were performed.

RESULTS AND DISCUSSIONS

CHEMICAL COMPOSITION

The chemical compositions obtained from the analyses of the samples AC1, AC2, BC1 and BC2 and the respective averages of alloys A and B are shown in Tables 3 and 4:

Table 3 – Chemical composition of alloy A.

Sample	% of Bulk Elements							
	To the	Yes	Mg	Faith	With	Zn	Minutes	In
AC1	98,59	0,446	0,355	0,330	0,065	0,051	0,047	0,022
AC2	98,61	0,438	0,348	0,320	0,063	0,052	0,047	0,023
Average	**98,60**	**0,442**	**0,351**	**0,325**	**0,064**	**0,051**	**0,047**	**0,022**

Source: Author (2024).

Table 4 – Chemical composition of alloy B.

Sample	% of Bulk Elements							
	To the	Yes	Mg	Faith	With	Zn	Minutes	In
BC1	98,88	0,420	0,363	0,195	0,0016	0,0045	0,047	0,026
BC2	98,88	0,427	0,363	0,193	0,0014	0,0048	0,047	0,025
Average	**98,88**	**0,423**	**0,363**	**0,194**	**0,0015**	**0,0046**	**0,047**	**0,025**

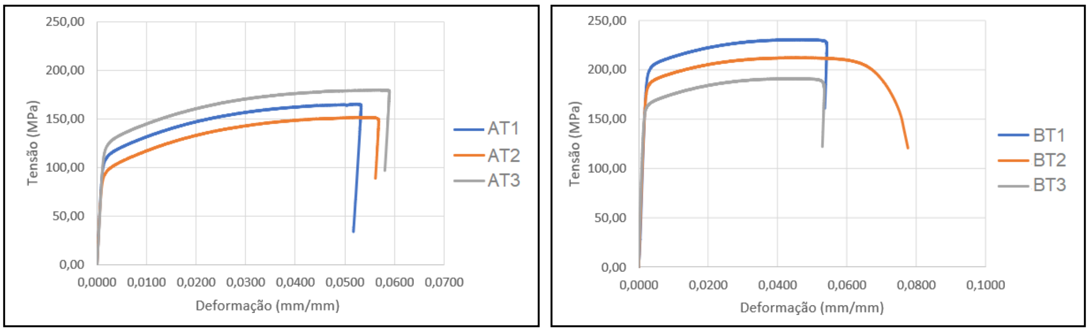
Source: Author (2024).

MECHANICAL TESTS

Traction

Figure 5 shows the stress-strain graphs obtained from the tests of the Alloy A and B specimens (without heat treatment)

Figure 5 – Stress-strain graph obtained from tensile tests.



Source: Author (2024).

The mechanical properties of alloy A obtained through tensile tests are shown in Table 5:

Table 5 – Mechanical properties obtained in tensile tests for alloy A.

Property	AT1	AT2	AT3	Average	Standard deviation
Modulus of elasticity (MPa)	77793,34	68738,64	79579,50	75370,49	5812,37
Yield strength (MPa)	115,35	100,60	127,83	114,60	13,63
Strength Limit (MPa)	165,13	151,45	179,55	165,38	14,5
Elongation (%)	5,32	5,68	5,90	5,63	0,29

Source: Author (2024).

The mechanical properties of alloy B obtained through tensile tests are shown in Table 6:

Table 6 – Mechanical properties obtained in tensile tests for alloy B.

Property	BT1	BT2	BT3	Average	Standard deviation
Modulus of elasticity (MPa)	82708,39	82325,91	71160,12	78731,47	6559,77
Yield strength (MPa)	198,50	184,67	164,95	182,71	16,86
Strength Limit (MPa)	230,73	212,32	191,21	212,42	19,76
Elongation (%)	5,43	7,76	5,35	6,18	1,37

Source: Author (2024).

Microdureza Vickers

Table 7 shows the Vickers microhardness measurements obtained in the tests for the A-alloy specimens:

Table 7 – Vickers microhardness measurements obtained in the A-alloy tests.

Measure	Microdureza Vickers (HV0,2)							
	AD1	AD2	AD3	AD4	AD5	AD6	AD7	AD8
1	56,60	36,70	55,70	50,10	76,20	81,10	81,70	61,70
2	57,80	36,40	52,70	48,40	79,00	80,80	83,60	65,50
3	600	36,20	56,50	48,40	81,70	81,70	78,80	60,60
4	58,70	35,00	51,00	48,00	77,60	82,30	83,20	66,80
5	59,10	32,40	54,80	49,90	81,40	79,30	80,80	67,30
6	54,70	36,80	51,80	50,10	76,00	79,60	81,70	66,80
7	56,70	37,90	55,00	53,00	77,30	84,20	82,30	64,20
8	56,00	41,50	54,70	49,60	79,90	84,20	82,60	64,70
9	58,30	39,50	54,50	48,90	77,10	81,70	84,80	63,40
10	56,70	38,8	53,00	50,40	76,8	84,8	80,80	66,00
Average	**57,46**	**37,12**	**53,97**	**49,68**	**78,3**	**81,97**	**82,03**	**64,70**
Standard deviation	**1,60**	**2,51**	**1,77**	**1,44**	**2,08**	**1,92**	**1,69**	**2,25**

Source: Author (2024).

Table 8 shows the Vickers microhardness measurements obtained in the tests for the B alloy specimens:

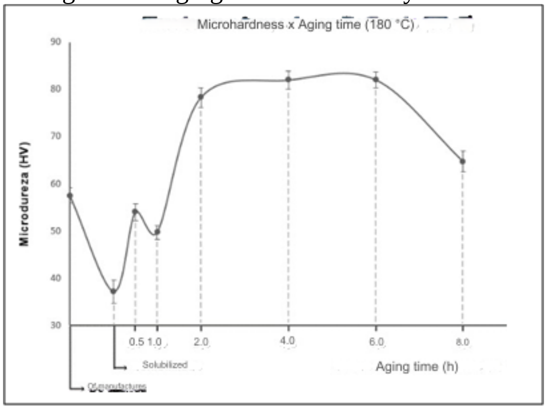
Table 8 – Vickers microhardness measurements obtained in the B alloy tests.

Measure	Microdureza Vickers (HV0,2)							
	BD1	BD2	BD3	BD4	BD5	BD6	BD7	BD8
1	78,20	41,10	42,30	44,20	45,50	63,40	73,80	59,80
2	74,40	37,60	42,30	46,00	45,90	64,00	72,50	61,90
3	83,60	38,60	43,80	45,20	46,00	64,00	74,60	57,10
4	77,10	37,30	42,70	45,00	46,40	62,80	75,20	58,30
5	76,00	39,10	43,30	45,90	45,70	61,60	73,80	60,60
6	80,50	39,50	41,10	44,90	46,70	62,60	73,10	59,40
7	80,80	36,70	44,50	44,20	46,80	63,00	72,30	59,60
8	81,40	39,60	43,10	45,20	47,20	62,40	74,40	61,60
9	75,70	40,00	43,20	46,20	45,70	63,40	73,30	60,80
10	77,90	37,80	43,70	46,70	48,30	61,90	71,50	60,60
Average	**78,56**	**38,73**	**43,00**	**45,35**	**46,42**	**62,91**	**73,45**	**59,97**
Standard deviation	**2,92**	**1,38**	**0,95**	**0,84**	**0,86**	**0,81**	**1,14**	**1,47**

Source: Author (2024).

From the data obtained, it was possible to plot the graph of the aging curves of the alloys, shown in Figure 6:

Figure 6 – Aging curve of the alloy studied.



Source: Author (2024).

MECHANICAL PROPERTIES

With the average measurements of Vickers microhardness obtained, it was possible to estimate the tensile strength and yield strengths of the alloys using equations.

Table 8 shows the estimated results for league A:

Table 8 – Resistance limits estimated by Petty's equations for alloy A.

Property	**Aging time (h)**						
	Solub.	**0,5**	**1**	**2**	**4**	**6**	**8**
Yield strength (MPa)	60,29	98,81	89,00	154,42	162,81	162,95	123,34
Strength Limit (MPa)	87,07	136,23	123,71	207,25	217,96	218,14	167,55

Source: Author (2024).

Table 9 shows the estimated results for League A:

Table 9 – Resistance limits estimated by Petty's equations for league B.

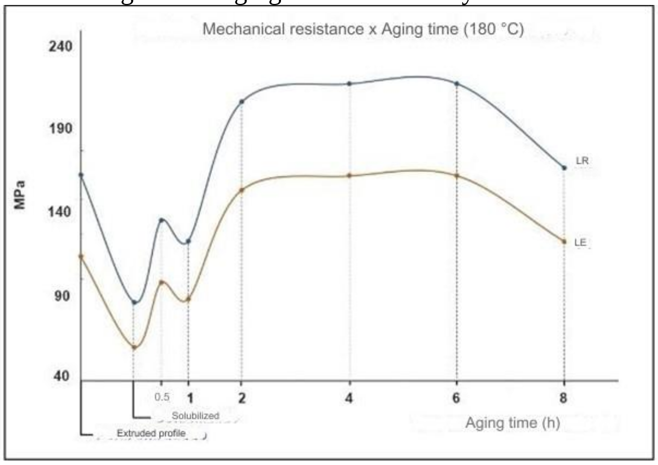
Property	**Aging time (h)**						
	Solub.	**0,5**	**1**	**2**	**4**	**6**	**8**
Yield strength (MPa)	60,29	98,81	89,00	154,42	162,81	162,95	123,34
Strength Limit (MPa)	87,07	136,23	123,71	207,25	217,96	218,14	167,55

Source: Author (2024).

The results obtained by Petty's equations were consistent with reality, considering that for the extruded profile material, the tested yield and strength strengths obtained the averages of 114.60 and 165.38 MPa, respectively, resulting in intermediate values between the times of 1 and 2 hours of aging, in the same way as the hardness of the material measured from the extruded profile.

To better illustrate the relationship between the microhardness and the mechanical strength of the alloy, Figure 7 shows a graph considering the yield and strength strengths tested for the extruded profile material and the values obtained through the hardness and Petty's equations after the heat treatments:

Figure 7 – Aging curve of the alloy studied



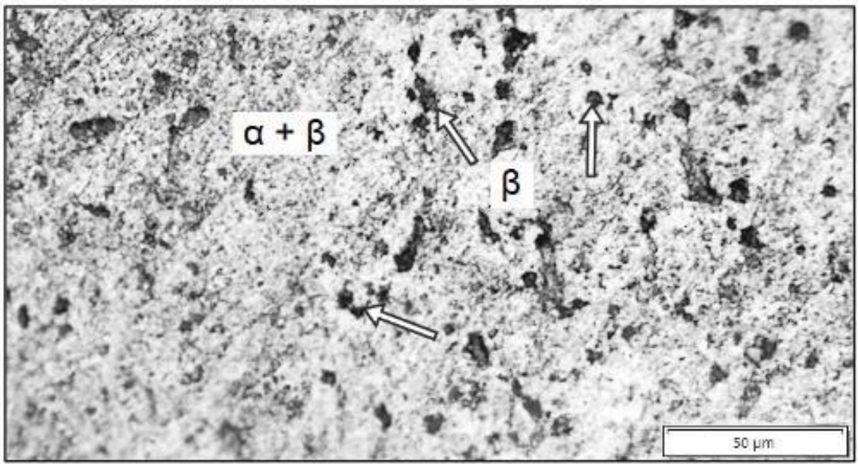
Source: Author (2024).

The curves for yield strength and strength limit are very similar to the microhardness curve presented in Figure 6, so it is possible to show the directly proportional relationship between the hardness and the mechanical strength of the alloy.

METALLOGRAPHY

Figure 8 shows the micrograph obtained from the M1 specimen (direct material from the extruded profile).

Figure 8 – Micrograph of the extruded profile material (20x approximation).



Source: Author (2024).

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It is possible to observe the α phase with a fine and uniform distribution of β precipitates, as well as several clusters of β precipitates (indicated by arrows) forming larger particles. Considering the microstructure and hardness of the extruded bar material, it can be said that this alloy was subjected to a heat treatment of about 8 hours of aging to be commercialized. The micrograph of the M2 specimen (solubilized and subjected to 0.5 h of aging) is shown in Figure 9:

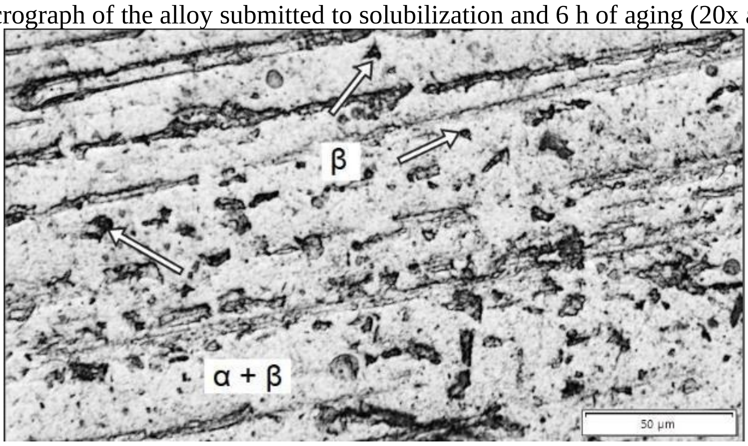
Figure 9 – Micrograph of the alloy submitted to solubilization and 0.5 h of aging (20x approximation).

Source: Author (2024).

As the M2 specimen has a relatively low hardness, particles of the material (from the preparation process for metallography) detached, forming several holes on the surface and making it impossible to observe the real microstructure of the sample.

Figure 10 shows the micrograph obtained for the M3 specimen (solubilized and subjected to 6 h of aging).

Figure 10 – Micrograph of the alloy submitted to solubilization and 6 h of aging (20x approximation).



Source: Author (2024).

Despite the marks left by the sanding of the sample, it is possible to observe the agglomerates of precipitates β (indicated by the arrows), and the phase α with a lower proportion of precipitates β distributed in it (compared to specimen M1), which is coherent, since it means that the precipitates were more concentrated in the agglomerate particles, justifying the higher hardness for the material aged for 6 hours.

CONCLUSION

Through the results of the chemical composition, it was possible to observe that the material is an alloy of the 6XXX series with the addition of iron in considerable amounts, in addition to some copper, zinc, manganese and titanium.

From the aging curve, it was found that the microhardness of the material reached the highest values in the interval between 4 and 6 hours of treatment, with a peak at 6 hours (82.03 HV0.2), with only 4.5% difference in microhardness between the times of 2 and 6 hours, which shows that the most advantageous aging time for industrial applications is 2 hours.

In addition, it was possible to observe that after 6 hours of aging for the temperature studied, the material began to undergo overaging, that is, its mechanical properties were reduced, showing that there is no use in maintaining the heat treatment for longer.

The estimates for yield strength and tensile strength of the material by means of the Petty equation show that the mechanical properties of the alloy increased after 2 hours of aging in relation to the factory material, in proportion to the microhardness.

The good response to precipitation hardening of the material may be a result of the influence of the presence of iron, manganese and copper in the alloy, which act by increasing the mechanical strength and improving the sensitivity of the material to heat treatments.

The micrographs obtained in the metallographic analysis confirm the presence of β precipitates in the middle of the α phase of the alloy. Comparing the micrographs and mechanical properties of the extruded profile material and after solubilization and aging for 6 hours, it can be seen that when the precipitates concentrate on the agglomerate particles, to a certain extent, the hardness and mechanical strength of the material tend to increase.

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