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INFLUENCE OF HEAT TREATMENT ON MICROSTRUCTURAL EVOLUTION AND MECHANICAL CHARACTERISTICS OF AA6061 ALUMINUM ALLOY

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Abstract. This study aims to understand the influence of heat treatment on behavior of AA6061 aluminum alloy at room temperature for various heat treatment. Two experimental parameters for this alloy are defined: micro hardness and the electrical resistivity, as a function of heat treatment at ambient temperature. The results show that the heat treatment conditions have an effective influence in mechanical properties of Al-Mg-Si aluminum alloy. This variation of the mechanical properties is the result of microstructural changes which have been observed using optical microscopy. When the material is subjected to a solution heat treatment followed by quenching and artificial aging, its mechanical properties, especially micro hardness and electrical resistivity, reach their highest levels and become very good compared to the other heat treatment applied to the same alloy.

Keywords: Aluminum alloy 6061, heat treatment, microstructural characterization, micro hardness, electrical properties.

Introduction

Mechanical properties of a material depend mainly on their chemical composition, parameters of precipitation process, and heat treatment (Sharma, Girish, Kamath, & Sathish, 1999). Aluminum alloys have attracted attention of many researchers, engineers and designers and had been used in different fields like industry, aeronautics, automobile sector. Especially, Aluminum-Magnesium-Silicon (Al-Mg-Si), denoted as 6XXX series, containing magnesium and silicon as its major alloying elements. AA6XXX Al-Mg-Si aluminum alloy has been extensively studied because of its technological importance in the automotive industry and its structural applications, for which demand is high (Belingardi & Obradovic, 2012; Dadbakhsh, Karimi Taheri, & Smith, 2010).

This series, AA6061, It is an age hardenable alloy, and can be significantly hardened by heat treatment. So, the mechanical properties are mainly controlled by the hardening precipitates contained on the material (Edwards, Stiller, Dunlop, & Couper, 1998; Murayama & Hono, 1999).

Heat treatment is the most important controlling factors used to enhance the mechanical properties of aluminum alloys. Improved mechanical properties of this alloy requires knowing the evolution of the microstructure at each stage of heat treatment. The T6 treatment involving solution heat treatment and quenching is a common method to increase characteristics of the alloy (Barresi, Kerr, Wang, & Couper, 2000).

The aim of the work presented in this paper is to evaluate the influence of the heat treatment process on the mechanical behavior and microstructural evolution in Al-6061 alloys containing additives of Copper; including micro hardness of the material at room temperature, while the electrical resistivity is also measured. The change of mechanical properties may due to metallurgical phenomena such as dissolution, precipitation.

For experimental convenience, the study will be limited to the solid state of the alloy. This means that the maximum temperature to be used is below 580 °C (solidus temperature for the AA6061). Furthermore, the mechanical characterization and microstructural observations will be carried out at room temperature after the heat treatment.

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1. Materials and methods

Al alloy 6061 is widely used in numerous engineering applications including transport and construction. This material can be heat treated to produce precipitation to various degrees. The Magnesium and silicon are the main alloying elements of these alloys, they ensure the hardening of the alloy by the formation of the compound Mg_2Si. It is commonly assumed that the generic precipitation sequence in Al-Mg-Si alloys is (Figure 1).

The material used in this study is an alloy based on aluminum grade 6061 with an excess of copper. Analysis of the chemical composition was performed using a spectrometry method. The Table 1 show the chemical composition.

For chemical composition we used optical emission spectroscopy, is an analytical chemistry techniques to analyze solid metals and alloys.

Samples for the mechanical tests were cut in cylindrical dimension of 30 mm height and 35 mm diameter (Figure 2), prior to testing, the samples were ground and polished.

1.1. Heat treatment

Heat treatment is the most important controlling factors used to enhance the mechanical properties and machinability of aluminum alloys. The improvement in the mechanical properties of Al alloys as a result of heat treatment depends upon the change in solubility of the alloying constituents with temperature.

Typical heat treatment used for the alloys from 6xxx series in the following steps, including homogenization and quenching (Gauthier, Louchez, & Samuel, 2016; Davis, 1993; Jorstad, 1980). Homogenization of the alloying elements in the solid state to obtain a homogeneous supersaturated structure, followed by the application of quenching with the aim of maintaining the supersaturated structure at ambient temperature (Jarco & Pezda, 2016; Pezda, 2012).

Figure 3 shows the major steps of the thermal heating applied for an Al-Mg-Si alloy with an excess of copper, which are normally used to improve the mechanical properties of aluminum.

In the present study, heat treatment is applied to a 6061 aluminum alloy, an age-hardening alloy, it can be strengthened appreciably by heat treatment.

The highest temperature to be studied is thus T = 550 °C, very close to the solidus temperature of 582 °C which should not be reached. To do so, an accurate control of the temperature has been set up.

The objective of the present study is to investigate the feasibility of heat treatment to the 6061 alloy with an excess of copper and to clarify the evolution of mechanical properties with heat treatment. So, after preparing samples, the alloy was solid-solution treated, quenching into water, and after heat treatment micro hardness and electrical resistivity was measured.

In order to study the mechanical properties behavior and the microstructure changes, the samples were divided into five groups and were given heat treatment by different procedures.

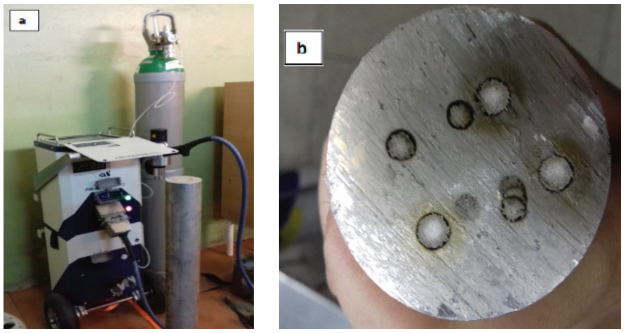

Figure 2. (a) Optical Emission Spectrometry device, (b) Burn marks on a workpiece used for the determination through Spectrographic Analysis

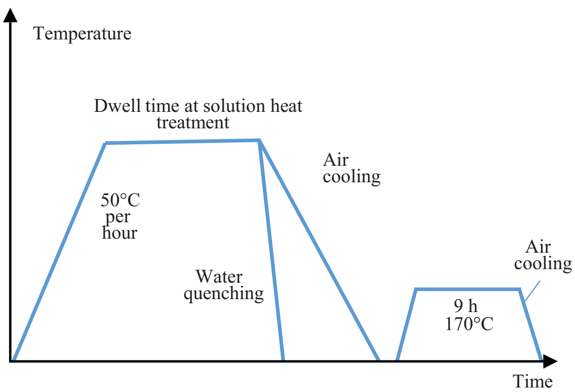

Figure 3. Diagram showing heat treatment process

Figure 1. Sequence of phase precipitation for Al-Mg-Si alloys

Table 1. The chemical composition of the AA6061-T6 alloy

Chemical composition / mass %													
Al	Mg	Si	Cu	Fe	Mn	Zn	Cr	Ni	Ti	Pb	Zr	N	Ag
Rest	1.32	0.67	1.54	0.47	0.19	0.18	0.16	0.13	0.03	0.05	0.01	0.17	0.01

The first heat treatment procedure, the alloy used is subjected to three-stage heat treatment. Treatment done to this alloy is the T6 treatment which consists of: Homogenization of 3 hours at 530 °C, a rapid cooling of the material in water having temperature 20 °C, and an aging at 170 °C for 9 hours.

The heat treatment of four samples, is done by homogenizing all samples at 450 °C and 550 °C, with a rise in temperature about 50 °C / hours, In this case, 9 h and 11 h are required to go from room temperature to 450 °C, 550 °C successively; and the second step is quenching at room temperature for 24 hours, and rapid cooling in water, some of them quenched immediately in water, and some are quenched in room temperature, like Table 2, shows.

Table 2. Representation of heat treatment conditions for each samples

Samples	Temperature (°C)	Heating rates 50°C/h	Dwell time (h)	Quenching
A	530	–	3	Rapid cooling in water
B	550	11	16	Rapid cooling in water
C	550	11	16	Room temperature
D	450	9	16	Rapid cooling in water
E	450	9	16	Room temperature

1.2. Microstructure characterization

The microstructure of each sample was examined using the optical microscopy of 6061 aluminum alloy is presented in the following pictures at various heat treatment applied. T6 heat treatment, 550 °C rapid cooling, 550 °C quench at room temperature, 450 °C rapid cooling and 450 °C quench at room temperature.

1.3. Mechanical characterization

In the present work, the experimental procedure consists of alloy preparation, measurements of the micro hardness and electrical resistivity of AA6061 alloy, and determination of the variation of electrical resistivity, the micro hardness with heat treatment for AA6061 alloy.

First, the material is given a solution heat treatment, usually followed by a quench. Heat treatment in different temperature were investigated in order to examine its positive or negative effects on the mechanical behavior of this material. The mechanical characteristics were measured in the end of every heat treatment.

1.4. Hardness test

In metal working, hardness generally implies resistance to penetration. It may, however, include resistance to scratching or cutting (Pethicai, Hutchings, & Oliver, 1983; Pharr, 1998). The possibility to carry out tests in so small scales makes this technique one of the tools chosen to characterize mechanical properties of materials (Carvalho et al., 2001; Lo & Bogy, 1998).

Micro hardness tests were carried out to evaluate the strength and ductility of AA6061 with an excess of copper. Vickers micro hardness (HV) was measured by imposing an imprint load 100 g, obj. 50 × for 10 second (Figure 4), at room temperature, using a Vickers micro hardness machine.

The test was conducted at room temperature (27 °C) on specimens previously heated to peak temperature of 550 °C and 450 °C with heating rates 50 °C/h in order to measure their mechanical properties, the measurement of hardness was taken at ten different places on each sample to obtain an average value of hardness (Figure 5).

This study will allow understanding the variation of the mechanical characteristics during heat treatment of the alloy.

The variation of Vickers hardness values of Al-6061 is plotted in Figure 6, showing the relationship between the hardness values and the heat treatment conditions.

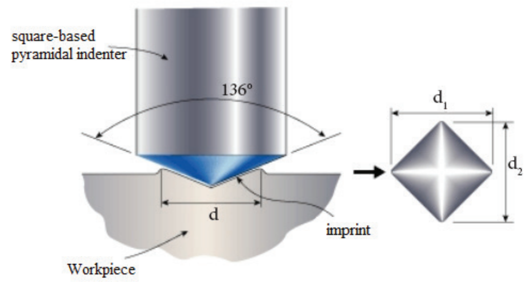

Figure 4. Schematic illustration of Vickers hardness test

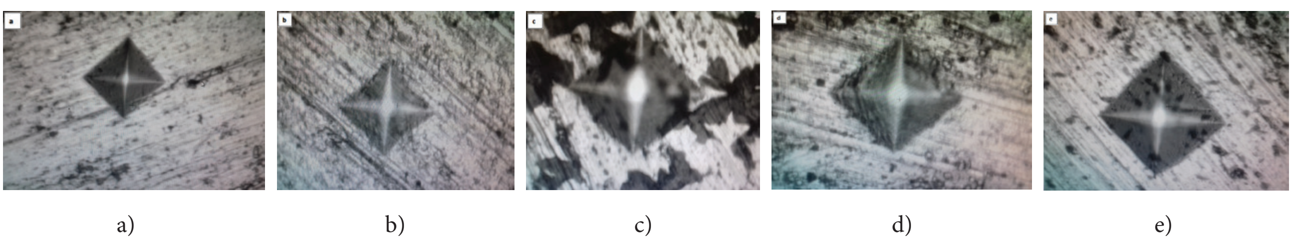

Figure 5. Vickers impression of Al-Mg-Si aluminum alloy on multiples heat treatment, (a) T6 heat treatment, (b) 550 °C rapid cooling, (c) 550 °C quench at room temperature, (d) 450 °C rapid cooling, (e) 450 °C quench at room temperature

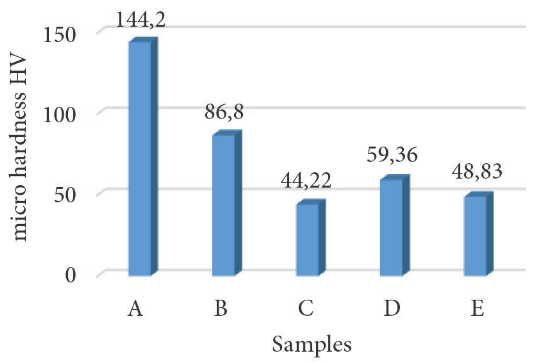

Figure 6. Shows the changes in Vickers hardness with the change of the heat treatment that we applied for each specimen

1.5. The Measurement of electrical resistivity

Resistivity ρ of a solid is an imperative physical property and is variously used for the characterization of materials. The value of electrical resistivity is affected by grain size, plastic deformation and heat treatment, but to a smaller extent compared to the effect of temperature and chemical composition (Rudnev, Loveless, Cook, & Black, 2002).

A two-point probe measurement is made by applying two electrical probes to the specimen. The heat treatment dependence of electrical resistivity of Al-Mg-Si alloy was measured by the two-point probe method at room temperature.

Experimentally, a resistance *R* is deduced from the ratio of an applied voltage U and the current *I*.

Thereby, the resistivity of the material is measured in Ωm, the voltage is in V and the current density in A. Only when the geometry of the set-up is well-known can the resistivity be accurately calculated, as we show above.

The electrical resistivity was measured by using the two-probe technique, whereby a cylindrical sample of diameter *D* = 35 mm and 150 mm for length, is loaded by a direct current *I,* using two constant electrical current of 412 A and 500 A.

Variations of electrical resistivity with different heat treatment for the Al-Mg-Si alloy are plotted in Figure 7. It can be seen from this Figs. the values of electrical resistivity for the Al-Mg-Si alloy are almost the same.

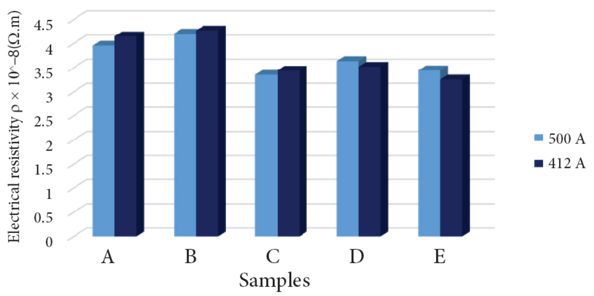

Figure 7. Variation of electrical resistivity, as a function of different heat treatment applied

2. Results and discussion

The mechanical properties of the 6000 series aluminum alloys, including hardness, electrical resistivity are carried out at room temperature. So, we studied the influence of the maximum temperature reached by using different heating rates on the microstructural evolution and on the mechanical characteristics of this alloy.

Results of the research concern effects of heat treatment parameters on the micro hardness and the electrical resistivity presented below.

6061 Al-alloy used in this investigation contains 1.324 Mg, 0.6771 Si and 1.544 Cu in weight percentage. Therefore, the increase in hardness after heat treatment could be cooperative precipitation of Al_2Cu and Mg_2Si phase particles.

The results presented in Figure 3, Figure 6, Table 1 and Table 2 indicate that the type of heat treatment applied has an influence in the mechanical characteristics especially micro hardness.

In the case of the 6061 aluminum alloy, the micro hardness **(HV)** and electrical resistivity (ρ) of the alloy were measured from directionally solidified samples.

2.1. Hardness

The micro hardness has been measured and the results presented in Figure 5, indicate that the micro hardness of the alloys was influenced by heat treatment applied; Because, as it can be seen in the graph, hardness reached their highest levels and become very good, compared to the other aluminum alloys specimens, when the material is subjected to a solution heat treatment followed by quenching and artificial aging; and The Al-Mg-Si alloy showed the lowest hardness values in the last heat treatment condition which water quenching was performed after solution treatment. This variation may be associated to a change in the microstructure.

2.2. Electrical

Additionally, the variation of electrical resistivity with heat treatment for Al-Mg-Si alloy was also measured at room temperature using a standard two-point probe technique for two different current.

The possibility that heat treatment might influence the resistivity significantly was tested. It can be seen for all the alloys the resistivity change is almost linear with the change in heat treatment.

From Figure 7, it can be seen that the electrical resistivity of aluminum alloy, slightly decrease or remain constant.

This means that heat treatment had a slight influence in the electrical resistivity.

Thus, the feature of the resistivity behavior is also independent of the heat treatment.

It can be seen that the first heat treatment has almost no influence on the electrical resistivity when as compared with the second series of heat treatment.

Conclusions

In this study, we investigate the relationship between changes in mechanical properties and microstructure evolution of Al-Mg-Si alloys when heat treatment is combined with precipitation hardening. This could help to make decision that applying heat treatment, have an influence in mechanical properties of the material.

The results can be summarized as follows:

1. Hardness in AA6061 varies in a complex manner. This variations for the alloy with various heat treatment, indicates that the hardness of AA6061 depends strongly on both the composition and the temperature of heat treatment.
2. Heat treatment effect on mechanical behavior of 6061 aluminum alloy.
3. The ideal heat treatment for this alloy was when the alloy is subjected to a solution heat treatment followed by quenching and artificial aging.
4. Al-Mg-Si alloy exhibited higher values of hardness when we applied the first heat treatment, and they are slightly lower when we applied the other heat treatment.
5. Comparatively, all heat treatment applied have a much smaller effect on the electrical resistivity changes of the material.

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TERMINIO APDOROJIMO ĮTAKA ALIUMINIO LYDINIO AA6061 MIKROSTRUKTŪRAI IR MECHANINĖMS SAVYBĖMS

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Santrauka

Šio tyrimo tikslas – ištirti skirtingo terminio apdorojimo įtaką aliuminio lydinio AA 6061 savybėms. Siekta nustatyti, kaip terminio apdorojimo temperatūra veikia lydinio mikrostruktūrą ir elektrinę varžą. Tyrimų rezultatai rodo, kad terminis apdorojimas turi įtakos mechaninėms Al-Mg-Si lydinio savybėms. Šios įtakos rezultatas – tai mikrostruktūros pokyčiai, nustatyti optiniu mikroskopu. Terminiam apdorojimui pritaikant grūdinimo ir dirbtinio sendinimo režimus, pasiekiamas didžiausias mikrokietumas ir elektrinė varža, palyginti su kitais terminio apdorojimo režimais.

Reikšminiai žodžiai: aliuminio lydinys 6061, terminis apdorojimas, mikrostruktūra, mikrokietumas, elektrinės savybės.