Mechanical properties analysis of Al-9Zn-5Cu-4Mg cast alloy by T5 heat treatment

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Abstract. The Improvement of mechanical properties of Al-9Zn-5Cu-4Mg cast alloy by T5 Heat treatment 200 °C during 200 hours was studied. Al-Zn-Cu-Mg alloy can be used in wide range of aircraft industry is based on the superior characteristic of this alloy. The main objective of this study is to investigate the influence of ageing process by performing tensile and hardness tests. The results revealed thatagingprocessisaffecting to the deployment of precipitationand it is indicate the formation of second phases $MgZn_2$ by atomic reactions that lead to the change of mechanical properties of Al-9Zn-5Cu-4Mgcastalloy..

1 Introduction

The development of the material strength is one of the most important subjects because it is the first characteristic to used in industrial applications. Aluminum is an important material that widely used in the many important structures since more than 80 years ago. Aluminum also is one of the metals with high performance that is most easily produced, which led to the need for production and maintenance costs are relatively low. The development of advanced aluminum makes this material can effectively cimpete with modern composite materials [1]. To improve the mechanical properties of aluminum and modify the microstructure can be done through alloying and heat treatment [2].

Aluminium alloys are increasingly used in many important manufacturing areas, such as military, automotive, aerospace because of their well known performance, well established design methods, manufacturing and reliable inspection techniques [3]. Although the increase in the use of composites reducing the role of aluminum in a certain extent, the use of high-strength aluminum remain indispensable in the construction of the airframe. It is also supported on the grounds that aluminum is a metal that is relatively inexpensive, light weight, heat treatable, and can be given a relatively high pressure.

The demand for aluminum alloys is growing rapidly due to the unique combination of properties that make it becomes one of the most versatile engineering and construction materials. Aluminium 7xxx series has a higher strength and mechanical properties if compared with other class of aluminum alloys [4]. High-strength age-hardened 7xxx series Al−Zn−Mg−Cu alloys are widely used for aircraft structures that is high demanding operating conditions. The important properties must be considered for these applications are corrosion and damage tolerance (e.g. fracture toughness and fatigue resistance), modulus, strength, and ductility. These important properties can be produced through a variety of alloys, the exact process or a combination of both [5].

Al-Zn based alloys have excellent corrosion resistance in variety of environments. The presence of aluminum in this alloy enhances corrosion resistance well-known of zinc , which is the main constituent of the alloy. Zn usually used in in the protective layer and the sacrificial anode because it is will improve the homogenity of the matrix in Aluminium.The present of zinc in aluminum also provides a solid solution. While [6]. The addition of zinc composition more than 3 wt% in aluminum alloys could increase the strength of aluminum alloys,while the bad influence of zinc are lowered toughness and increasing brittleness. However, the addition zinc element under 3 wt% considered useless [7]. The present of 9% Zn will increase the strength but also will decrease the ductility in aluminium alloys. It is happen through the mechanism of solid solution strengthening, where Zn dissolved as a substitute in the lattice of aluminum atoms.

The addition of magnesium provides good weldability and good corrosion resistance. The present of copper in aluminium alloys is increasing matrix hardness so it generates i the improvement in the machinability. Copper take the good impact on the strength and hardness of aluminum alloys, in both heat treated and not heat treated condition [8]. The proper Mg addition amount is beneficial to enhance the mechanical properties of the graphite particles reinforced aluminum alloy matrix composites and the abrasion resistance of

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the materials due to uniformaly distribution of hard particles and reduction of friction coefficient [9].

Zinc combined with copper and / or magnesium will generate the heat-treatable compositions which contributed to the increased hardness and strength in the heat treatment because the presence of four major intermetallic phases that are expected in commercial Al-Zn-Cu-Mg alloys including η ($MgZn_2$), T ($Al_2Zn_3Mg_3$), S (Al_2CuMg), θ (Al_2Cu), Al_7Cu_2Fe, $Al_{13}Fe_4$, and Mg_2Si phases [4-6]. T and η phase are often present in solid solution with the presence of the four elements [10,11].

There are some artificial aging processes commonly applied to aluminium, in this experiment we were used T5 artificial aging. The difference of T5 from T4 and T6 is the heat treatment process passed without any solution treatment . The advantages of no solution treatment are significant energy savings and reduce distortion in components [12]. T5 is an artificial aging that are commonly used in increasing reinforcement through hardening precipitates. Benefits of T5 heat treatment can be lost when done quenching after casting. When the temperature increase, the rate of nucleation and growth of precipitates can be accelerated. The increase in strength occurs in line with the decrease in ductility on dendritic material.

The main objective of this study is to investigate the influence of aging process in a long period of Al-9Zn-5Cu-4Mg cast alloy by performing tensile and hardness tests. The results of a study of the heat treatments 200° C for 200 hours on the mechanical properties, it is possible to determine reactions, material behaviour for long period used and also determine conditions necessary to achieve optimum mechanical properties and performance.

2 Experimental details

2.1 Preparation of Al-9Zn-5Cu-4Mg Alloy

Al-9Zn-5Cu-4Mg cast alloy was prepared through the addition of measured amounts of Zn, Cu, and Mg to the molten aluminum in crucible grafit with melting temperature measured stable in 750° C. Aluminium and alloy composition weight of the charge is 4.5 kg with calculation of mass balance of each alloy and the possible evaporation by 14% Zn and Mg 10% are as shows in Table 1:

Table 1. Mass Balance of Aluminum Alloys

Al	Zn (0,09)	Mg (0,04)	Cu (0,05)	Zn Assumed evaporated 14%	Mg Assumed evaporated 10 %
3615	405	180	225	461,7	198

The melting process begins with preheated the furnace until reaching the specified temperatures. The next process is inserting aluminium into crucible for approximately 1 hour until it is completely dissolved. Then then followed by addition other elements Cu, Zn at muffle furnace for 2 hours or until all elements also completely dissolved.

The use of low-temperature condition can help minimize the presence of hydrogen in liquid aluminum. Degassing process is carried out to remove impurities dissolved in the molten metal using argon gas. The molten metal degassed for 2 minutes to lift impurities that contained in the molten metal and bring it to the surface.

Permanent mold made from mild steel and coated with clay to facilitate the release of cast product from the mold. After the molten metal have solidifying as a whole, the casting product then released from the mold and followed by a visual inspection on surface product.

Cast products then tested for chemical compositions analysist by using emission spectrometer and the result is shown in Table 2.

Table 2. Main Chemical Compotitions of Al-9Zn-5Cu-4Mg castalloy

Zn	Cu	Mg	Fe	Al
[%]	[%]	[%]	[%]	[%]
9.63	5.52	4.43	0.14	Rest

Analysis of chemical composition was performed by using of spectrometry method (emission spectrometer PMI – Master Pro Oxford instrument analytical GmBH type).

2.2 Cutting Samples

The cast product then cutted according to requirement of the testing to be performed. Cutting process was conducted by using a metal cutting saws 9" Type Krisbow KW1500053. Then followed with cutting process that using hand grinder to produce small samples. Refinering surface was conducted by sandpapers #120 #200 #400 #600 #800 and #1000 to ensure the surface of samples completely smooth.

2.3 Heat treatment

The experiment were prepared in two conditions, as-cast and heat-treated alloy. The as-cast samples were not conducted by the heat treatment process, whilet he heat-treated samples were heated in 200 °C for 200 hours with Heater furnace Hofmann K1. Cooling process carried out in the heater furnace for ± 3 hours until the temperature returns to normal. Time required to heating the samples was 20 days with range of warm-up time approximately 10 hours each day.

2.4 Tensile test

Tensile test carried out by using *Universal Testing Machine Tokyo Testing Machine* MI7G tipe RAT-30P. Testing was conducted by using standard JIS Z 2201. Both as-cast and heat-treated conditions were tested at room temperature in three samples.

2.5 Hardness test

The samples were tested using Vickers Hardness Tester VKH-2E which is based on an assessment of the indenter penetration pyramid. Preparation of the test specimen was conducted by cutting the sample, heat treatment, and surface smoothing with sandpaper # 80, # 120, # 240 and # 800. The change of characteristic and strength of the aluminum alloy that influenced by Artificial aging can be seen from the results of hardness tests. Hardness test was performed in the two conditions of the samples, as-cast and heat treated alloys. Hardness testing was using load 10 kgf. Hardness (HV) obtained by using Equation 1 below :

$$HV = \frac{2p\sin\left(\frac{\theta}{2}\right)}{L^2} = 1{,}854\ \frac{P}{L^2} \qquad (1)$$

2.6 Metallography observations

Microstructure observation were conducted through the process of metallography that are sample selection, cutting, mounting, grinding, polishing, etching and observation using optical microscope. Metal polishing was using TiO_2 and followed by etching using a mixture of 12.5 ml 8 ml HNO3 + HF + 85 ml of water. Metallography observations in this research are using an optical microscope, SEM and EDS.

3 Results and discussions

3.1 Mechanical characteristics

Investigation results of the mechanical characteristics of the Al-9Zn-5Cu-4Mg cast alloy are presented in Table 3. Based on data below, as-cast alloy has higher hardness value than heat-treated alloy. It is also proved by the reduction of the ultimate tensile strength value in heat treated samples.

The deployment of precipitation that caused by the heating process and the high content of Zn affecting to the brittleness and the toughness of heat treated alloy, it makes the ultimate tensile strength and hardness value were not exceed the value of as-cast alloy.

Table 3. Mechanical Properties of as-cast and heat treated Al-9Zn-5Cu-4Mg cast alloy

Al-Zn-Cu-Mg Cast Alloy	Tensile Strength (MPa)	Elongation %	Hardness, VH
As -cast	447	0.8	136
As –cast	446	1.1	136
As –cast	450	0.9	137
Heat treated T5	453	1.4	138
Heat treated T5	457	1.1	139
Heat treated T5	465	1.3	142

Artificial aging that conducted in a long period will present the second phase precipitates that affect to the mechanical properties of aluminum alloy casting. Wherein said second phase acts as a barrier that causes dislocation shift increasingly difficult when it is loaded but in the other hand it acts as embrittled phase that decrease the toughness and strenght of alloy.

The difference values in mechanical testing at any point due to unevenly distribution of atoms in aluminum cast and possibility of impurities presence that may occur due to error in casting process.

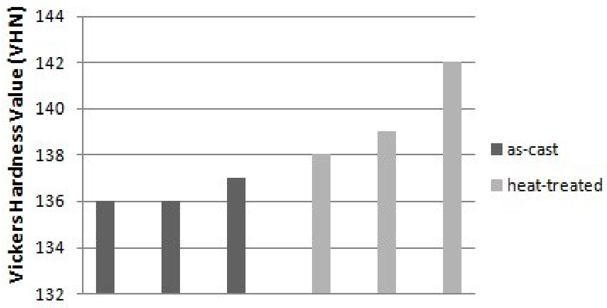


Fig. 1. Heat Treatment effects on hardness of Al-9Zn-5Cu-4Mg

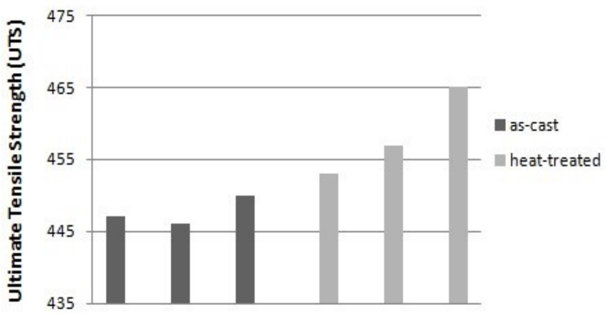


Fig. 2. Heat Treatment effects on tensile strength of Al-9Zn-5Cu-4Mg

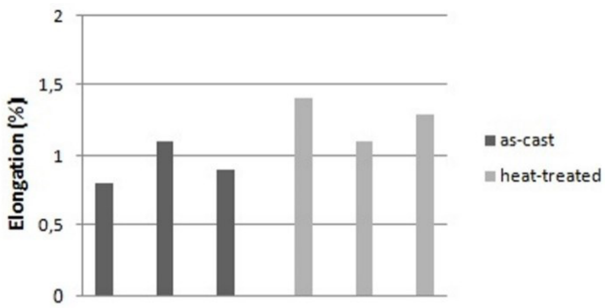
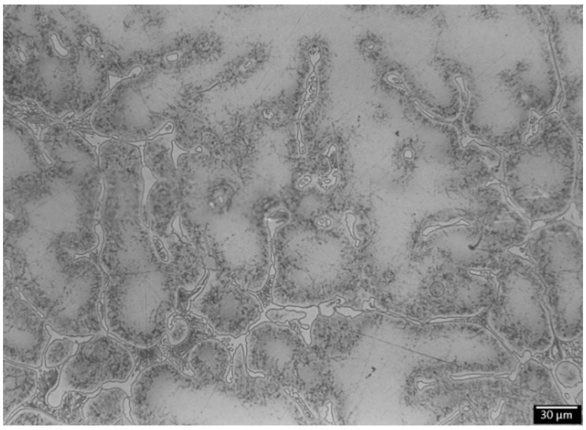


Fig. 3. Heat Treatment effects on elongation of Al-9Zn-5Cu-4Mg

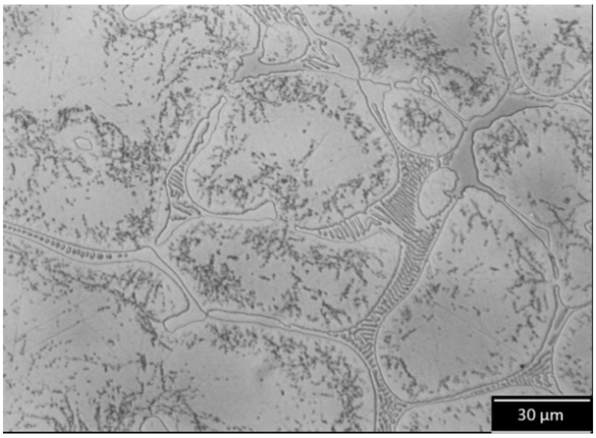
3.2 Microstructure characteristic

On Fig 4 and 5, the heating process leads precipitation on the grain boundaries spread to all over dendrite. Based on EDS result of as-cast Al-9Zn-5Cu-4Mg alloy (see Table 3 and table 4) shows the presence of $Mg_3Zn_3Al_2$ precipitate dispersed finely in Aluminium, and there are also the presence of $Mg_3Zn_3Al_2$, $CuAl_2$, $CuMgAl_2$. The presence of Fe element as impurities made of aluminum become coarse grains, reducing the ductility of alloy [10] and leads the presence of Cu_2FeAl_7.The microstructure of heat-treated cast Al-9Zn-5Cu-4Mg alloy shows the presence of non-uniformly coarse grains of $MgZn_2$ (see table 5) in dendrite.

Fig 6 and Fig 7 are shown the microanalysis report by Energy - dispersive spectroscopy (EDS) of dendrite and grain boundary of as-cast alloy. While Fig 8 and Fig 9 are shown the microanalysis report by Energy - dispersive spectroscopy (EDS) of dendrite and grain boundary of heat-treated alloy.

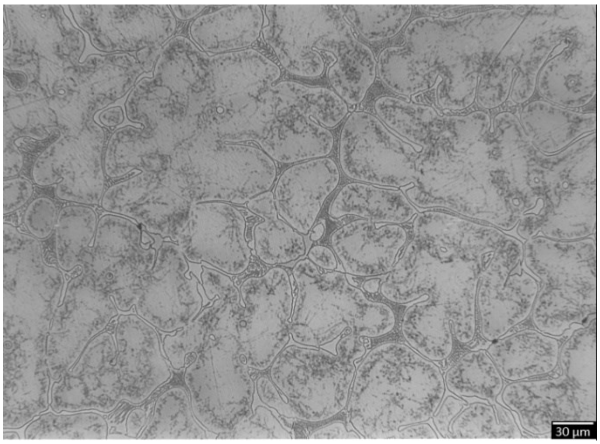


(a)

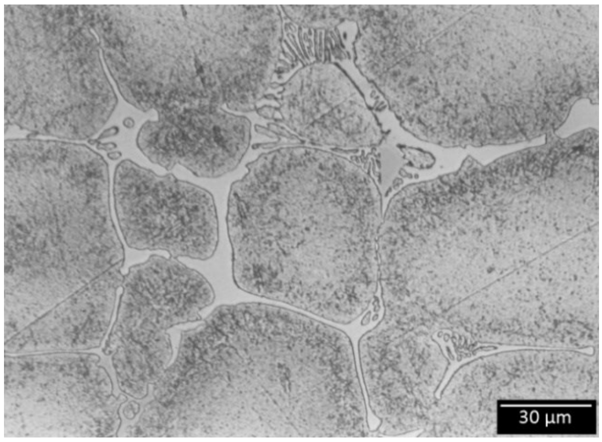


(b)

Fig. 4. Microstructure of as-cast Al-9Zn-5Cu-4Mg alloy (a) magnification 200x (b) magnification 500x



(a)



(b)

Fig 5. Microstructure of heat-treated Al-9Zn-5Cu-4Mg alloy (a) magnification 200x (b) magnification 500x

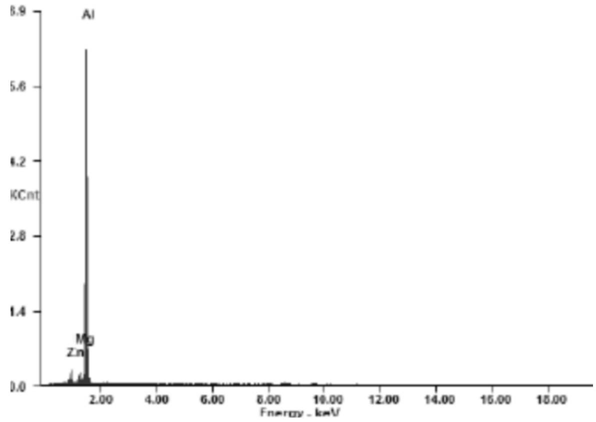


Fig 6. the microanalysis report by Energy - dispersive spectroscopy (EDS) of dendrite as-cast alloy

Table 4. Summaryof EDS observation on dendrite as-cast Al - 9.7Zn - 5.5Cu - 4.5Mg cast alloy

No	Average elementwt.%			Phase may be formed*
	Al	Zn	Mg	
1	90.34	6.81	2.85	$Mg_3Zn_3Al_2$
2	89.40	7.30	3.30	$Mg_3Zn_3Al_2$
3	89.65	7.32	3.03	$Mg_3Zn_3Al_2$

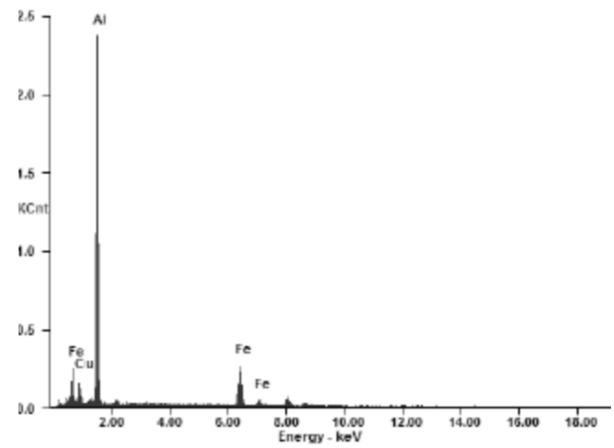


Fig 7. the microanalysis report by Energy - dispersive spectroscopy (EDS) of grain boundary as-cast alloy

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Table 5. Summaryof EDS observation on grain boundary as-cast Al - 9.7Zn - 5.5Cu - 4.5Mg cast alloy

No	Average elementwt.%					Phase may be formed*
	Al	Zn	Mg	Cu	Fe	
1	68.59	-	-	11.31	22.09	Cu_2FeAl_7
2	24.72	27.29	23.85	24.14	-	$Mg_3Zn_3Al_2$, $CuAl_2$, $CuMgAl_2$
3	57.83	10.68	13.67	17.82	-	$Mg_3Zn_3Al_2$, $CuAl_2$, $CuMgAl_2$

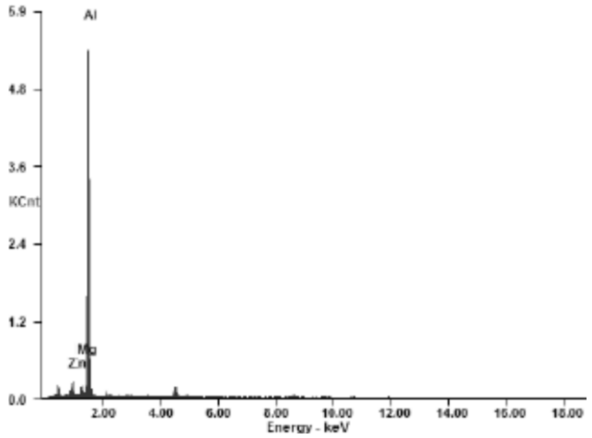

Fig 8. the microanalysis report by Energy - dispersive spectroscopy (EDS) of dendrite heat-treated alloy

Table 6. Summaryof EDS observation on dendrite heat-treated Al - 9.7Zn - 5.5Cu - 4.5Mg cast alloy

No	Average elementwt.%			Phase may be formed*
	Al	Zn	Mg	
1	90.05	7.08	2.87	$Mg_3Zn_3Al_2$
2	89.38	3.09	7.53	$MgZn_2$
3	89.91	2.75	7.34	$MgZn_2$
4	90.52	2.75	6.73	$MgZn_2$

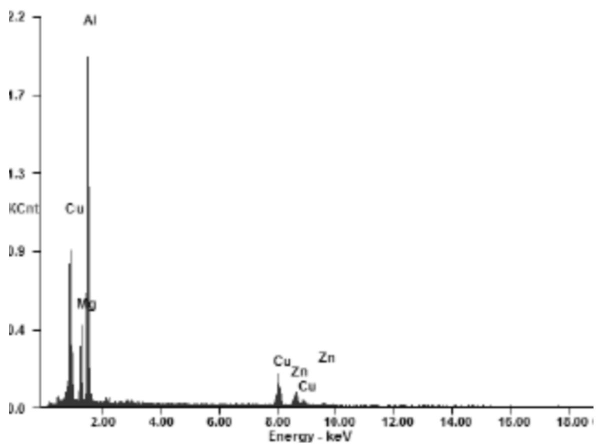

Fig 9. the microanalysis report by Energy - dispersive spectroscopy (EDS) of grain boundary heat-treated alloy

Table 7. Summaryof EDS observation on dendrite heat-treated Al - 9.7Zn - 5.5Cu - 4.5Mg cast alloy

No	Average elementwt.%					Phase may be formed*
	Al	Zn	Mg	Cu	Fe	
1	69.51	-	-	7.70	22.79	Cu_2FeAl_7
2	25.97	25.02	25.2	23.82	-	$Mg_3Zn_3Al_2$, $CuAl_2$, $CuMgAl_2$
3	57.83	10.68	13.67	17.82	-	$Mg_3Zn_3Al_2$, $CuAl_2$, $CuMgAl_2$

*) Prediction phase based on the phase data thatmayappear in Al-Zn – Mg [13]

Aluminium 7xxx series are susceptible to embrittlement because of microsegregation of magnesium zinc (MgZn2) precipitates which may lead to failure of components produced from them. This microsegregation and inherent residual stresses have serious deleterious effects on mechanical properties [14].

Heat treatment of Al-Zn-Mg-Cu alloys led to formation of $MgZn_2$ intermetallic phase in the structure. Many coarse intermetallic phases like $Al_2Mg_3Zn_3$, Mg_2Si, $MgZn_2$, AlCuMg, Al_7Cu_2Fe, Al_2Cu, and $Al_{13}Fe_4$ can be formed below the solidus line during solidification as a result of solute redistribution of metals. There was no room for solute redistribution of Mg and Zn and hence microsegregation of $MgZn_2$ was not formed.

The T5 hea-treated alloy has the highest hardness and strength because of the presence of coherent $MgZn_2$ precipitates in its structure which was developed during aging. The highest hardness value developed by age hardened samples can be attributed to precipitation of coherent and finely dispersed $MgZn_2$ phases which serves as foreign inclusion in the lattice of the host crystal in the solid solution ,it causes more lattice distortions which makes the alloy harder.

4 Conclusion

Based on the results of mechanical testings and microstructure observation,the impairment of the strength and toughness of the heat-treated Al-9Zn-5Cu-5Mg cast alloy were caused of the deployment of precipitation from the edge of dendrite to all over dendrite.It is also caused by the presence of embrittled phase $MgZn_2$ that dispersed evenly throughout the dendrite due to the heat treatment process that conducted at temperature 200° C for 200 hours. T5 heat treatment operation was found to improve hardness value, yield and ultimate tensile strengths with a corresponding decrease in ductility.

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