Effect of Heat Treatment on Hardness and Corrosion Behavior of 6082-T6 Aluminium Alloy in Artificial Sea Water

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Abstract: Aluminium alloys of 5xxx and 6xxx series are commonly used in marine environment due to their good corrosion resistance. 6xxx series alloys show better mechanical properties and good weldability but have comparatively less corrosion resistance. Alloy 6082 has highest strength among 6xxx series, which can be further increased to get peak strength by T6 tempering. Also it has high corrosion resistance due low copper content. Second phase particles formed during precipitation hardening heat treatment gets randomly distributed throughout the grains and helps to increase hardness and corrosion resistance of metal. In this study various experiments of precipitation hardening are done on aluminium alloy 6082-T6 to increase its hardness and corrosion resistance. Effect of time and temperature of solution heat treatment and artificial aging on the hardness and corrosion resistance of alloy is analyzed. Also effect of temperature of corrodent on corrosion behavior is determined. Hardness is measured on Rockwell E scale. Immersion corrosion test is carried out to find general corrosion resistance. Microstructures of hardened as well as corroded samples are analyzed by means of optical microscopy. The results show that during precipitation hardening process, the grain size and grain structure changes; both of which are responsible for change in hardness. Hardness increases with increasing artificial aging time up to 12 Hrs. It is also observed that corrosion resistance of alloy is not only dependent on chemical composition and grain structure of exposed alloy but also on composition of corrodent (e.g. pH, temperature, halide concentration, velocity, aeration). The increase of hardness and corrosion resistance increases alloy strength and life in sea water.

Key words: 6082-T6 Al alloy, hardness test, immersion corrosion test, precipitation hardening.

1. Introduction

Aluminium is adopted for the fabrication of modern ships, due to its low density, high strength to weight ratio, good weldability, corrosion resistance and better mechanical properties. Aluminum alloys of 5xxx and 6xxx series are widely used in marine industry owing to their light weight, high strength, good corrosion resistance and weldability. 5xxx-series have shown excellent corrosion resistance in marine services. However, there is a general reluctance to place 6xxx-series alloys in similar service [1]. Although, 6xxx series alloys show better Mechanical properties than 5xxx series alloys, their corrosion resistance is comparatively low. Alloy 6082 has highest strength among 6xxx series, which can be further increased by T6 tempering [2]. Also it has high corrosion resistance due to low copper content which can be further

increased by precipitation hardening heat treatment.

The increase in strength during precipitation hardening heat treatment is due to precipitation of different types of metastable phases forming in aluminium solid solution. General requirement for precipitation strengthening of supersaturated solid solution (SSSS) involves the formation of extremely small uniformly dispersed particles of a second phase within the original phase matrix [3]. It is assumed that the precipitation sequence during ageing in 6xxx series aluminium alloys occurs according to the general scheme described for the ternary Al-Mg-Si alloys:

$$\text{Supersaturated solid solution } \alpha\ (\text{Al}) \rightarrow \text{GP zones} \rightarrow \beta'' \rightarrow \beta' \rightarrow \beta\ (Mg_2Si)$$

The supersaturated solid solution of α (Al) is formed upon rapid cooling from the solution heat treatment temperature to room temperature. The clusters of Mg and Si atoms are formed as coherent matrix in GP zones. Next, partially coherent, very fine needles of metastable β" phase and rod shaped metastable β' phase are getting formed. The final product of decomposition is the equilibrium β (Mg_2Si) phase [4]. Further modifications in precipitate phases can be obtained by varying temperature and time (duration) of solution heat and artificial aging.

The corrosion resistance of 6xxx series aluminium alloys depends on oxide film formation. Under normal atmospheric conditions aluminium reacts with water to form $Al(OH)_3$ which gets adsorbed on the alloy surface forming oxide film. This oxide film is non-uniform, thin and non-coherent; however it is naturally self-renewing and accidental abrasion or other mechanical damage of the surface film is rapidly repaired. Therefore, it imparts a certain level of protection under normal conditions. When exposed to environments containing aggressive halide ions, such as chlorides (Cl^-), aluminium reacts with chloride ions forming $AlCl_3$ which goes into the solution and hydrolyzes therein, leaving bare active sites available for attack [1–5-6]. This type of corrosion is known as pitting corrosion.

In sea water 5xxx series alloys shows fairly good resistance to both general and localized corrosion. However, 6xxx series aluminium alloys show lower resistance to localized corrosion. They are more prone to pitting corrosion. Corrosion resistance of these alloys depends on rate of formation and breakdown of oxide film. Intensity of corrosion attack depends on chemical composition of both exposed alloy and corrodent. Inclusions, second phase particles, their size and grain structure also affects corrosion rate of alloy. In the marine environment intended service life also depends on composition of sea water. pH, velocity, temperature, time of exposure, aeration of sea water also affects corrosion rate. Simple immersion corrosion test is useful to find general corrosion rate [7].

In this study both hardness and corrosion resistance of 6082-T6 Al alloy is evaluated. Effect of variation in solution heat treatment temperature and aging time on hardness of specimen has been evaluated. Corrosion behavior of alloy is studied at various water temperatures keeping all other parameters constant. Also effect of second phase particles formed, due to precipitation hardening heat treatment, on hardness and corrosion rate is studied. Both hardness and corrosion resistance are found to be primarily dependant on composition and grain structure of alloy.

2. Experimental Procedure

Aluminium alloy 6082-T6 is used for test, alloy composition of which is given in Table 1. Material characteristics and general mechanical properties of alloy are given in Table 2. [2]

Table 1. Chemical Composition of 6082 Al Alloy

Alloying Element	Mg	Si	Mn	Cu	Cr	Zn	Ti	Fe	Al
%ge	0.60-1.20	0.70-1.30	0.40-1.00	0.10	0.25	0.20	0.10	0.50	Balance

Table 2. General Properties of 6082-T6 Al Alloy

Material	Density (g/cm^3)	Melting Point (liquidus) (^0C)	Yield Strength (MPa)	Tensile trength (MPa)	Elongation in 50 mm (%)
6082-T6	2.66	600	280	315	12

The specimens are cut from sheet metal in dimensions (25*50*03) mm [5]. The surface of all specimens is cleaned with acetone and then dried and saved in sealed container for next step.

2.1. Heat Treatment

Precipitation hardening is the heat treatment performed on samples, to increase hardness. To short or to long aging cycle lowers tensile properties and hence avoided. 3 groups each containing 5 samples are prepared i.e. cleaed with acetone and dried. Samples of 3 groups are solution heat treated, in muffle furnace, for 12 hours at 3 different temperatures viz. 500°C, 520°C, 560°C respectively. Heated specimens are then quenched with water at room temperature. 4 samples from each group are then artificial aged at temperature 160°C for 3, 6, 9, 12 hours [8]-[9]. After artificial aging the specimens are cooled in room temperature air. Over aging reduces hardness and tensile strength of material. Hence aging above 12 Hours is avoided.

2.2. Hardness Test

Aging Time and Heating temperature are two variables in this study. Rockwell hardness test of specimens are carried out using Rockwell E Scale, 100kgf load and 1/8" ball Indenter. A total of five readings are taken on each sample (i.e. for every ageing time at the respective temperatures) and average value is calculated. From each group, sample with highest hardness value is selected for optical microscopy. For optical microscopy etchant is prepared using 1gm NaOH in 100 ml H_2O. Specimen were polished using 400, 800, 1000, 1200 grit papers, followed by diamond Polishing using 3µ diamond pest and then on OP-S using A_2 struers.

2.3. Immersion Corrosion Test

From above 3 groups, the samples giving highest hardness values in hardness test are selected for corrosion experiment. Samples of untreated alloy are tasted to check corrosion resistance of untreated alloy at various water temperatures. Corrosion test is carried out using artificial sea water within the temperature range of 30^0C to 50^0C [6]. According to testing parameters a modified test rig is used to carry out immersion corrosion test [5] - [10]. Samples are divided in 4 groups viz. A, B, C, D. Each group contains 7 samples. Group A contain untreated samples, whereas groups B, C & D contain samples of alloy solution heat treated at 500^0C/12hrs, 520^0C/12hrs, 560^0C/12hrs respectively. Only the samples artificially aged at 160^0C for 12hrs are selected from groups B, C, D; since they give maximum hardness. Artificial sea water is prepared keeping pH value 8.33 [11]. Test is carried out at 7 different water temperatures viz. 30^0C, 34^0C, 37^0C, 40^0C, 44^0C, 47^0C, 50^0C. Each test is carried out for 72 hrs keeping flow rate of water 90rpm. Test specimens of size (25*50*03) mm are cleaned with acetone and weighed before and after immersing in artificial sea water for test. Difference between initial and final weight is recorded to measure weight loss.

Corrosion rate is calculated from weight loss [5]. Microstructures of specimen are taken to analyze pit morphology.

3. Results and Discussion

Effect of heat treatment on hardness is tested first. Samples with highest hardness values are then analyzed using microstructures from optical microscopy.

3.1. Hardness Test Analysis

Hardness value of untreated test specimen is 68 HRE. This value is selected as a reference to compare variation in hardness with further heat treatments. Table 3 shows the changes in hardness values with variation in heating temperature and aging time.

Table 3. Hardness Results for Specimens Solution Heat Treated at 500^{0}C, 520^{0}C and 560^{0}C Temperature for 12 Hours and Aged at Temperature 160^{0}C for Various Aging Time Periods

Solution heat treatment temp. (^{0}C)	Aging time				
	0 Hrs	3 Hrs	6 Hrs	9 Hrs	12 hrs
500	52	63	68	72	76
520	58	60	79	86	92.5
560	65	68.5	74.5	76	85.2

Hardness values of samples which are not artificially aged but only solution heat treated are shown in column of 0 hours. For all the samples heated at 500^{0}C, 520^{0}C, 560^{0}C hardness varies with aging time. From Fig. 1 it can be clearly seen that at higher aging time period precipitation hardening at 520^{0}C gives highest hardness, whereas precipitation hardening at 500^{0}C shows lowest hardness.

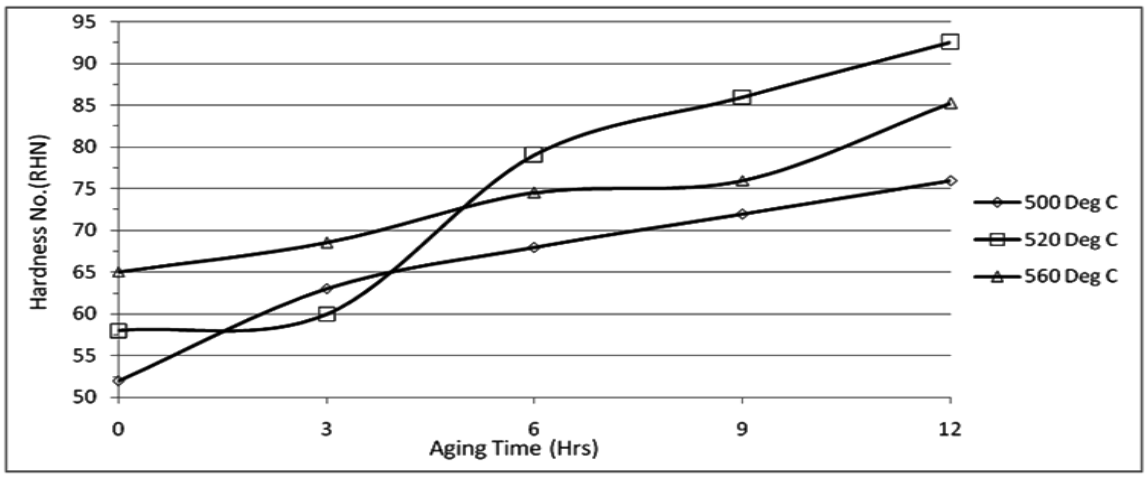


Fig. 1. Effect of aging time on hardness of samples solution heat treated at 500^{0}C, 520^{0}C, 560^{0}C for 12 hours and aged at 160^{0}C

Fig. 2 gives the microstructures under optical microscopy for the samples solution heat treated at 500^{0}C, 520^{0}C, 560^{0}C for 12 hours followed by artificial aging at 160^{0}C for 12 hours.

Fig. 2(a) shows distorted grain structure which results into low hardness value for specimen precipitation hardened at 500^{0}C. Fig. 2(b) shows uniform grain structure with very small grain size. With decrease in grain size hardness goes on increasing, which is the reason of having highest hardness value for specimen precipitation hardened at 520^{0}C. Fig. 2(c) shows uniform grain structure with larger grain size. Intermidiate hardness value of this specimen is because of its large and coarse grains.

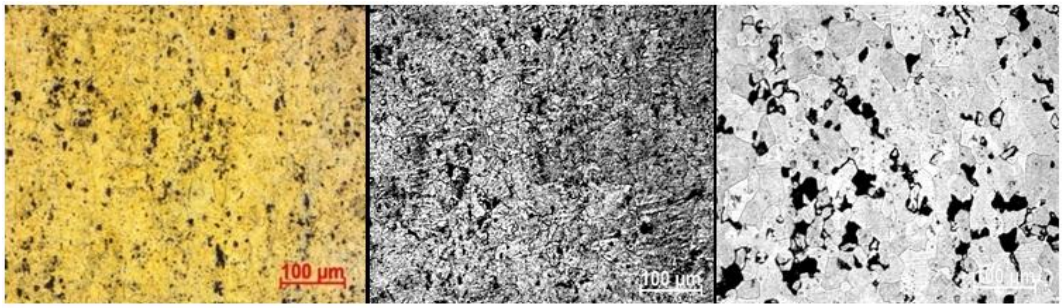


Fig. 2. Microstructures of samples heat treated at (a) 500^{0}C/12hrs, (b) 520^{0}C/12hrs, (c) 560^{0}C/12hrs followed by artificial aging at 160^{0}C/12 hours

3.2. Corrosion Rate Calculations and Results

Table 4 shows the variation of corrosion rate with water temperature. For lower water temperatures group C shows least corrosion rate. For higher water temperatures group D shows comparatively low corrosion rate. Group A & B shows higher corrosion rate for all water temperatures.

Table 4. Effect of Water Temperature on Corrosion Resistance of Specimens of Untreated Alloy and Specimen Precipitation Hardened at 500^{0}C, 520^{0}C, 560^{0}C

Sample Group	Test No.	Water Temp. (^{0}C)	Weight Loss (mg)	Corrosion Rate (mm/yr)
A (untreated)	1	30	27	0.654
	2	34	28	0.742
	3	37	34	0.986
	4	40	27	1.055
	5	44	23	1.127
	6	47	19	0.986
	7	50	14	0.954
B (500^{0}C)	1	30	26	0.937
	2	34	31	1.125
	3	37	34	1.226
	4	40	32	1.143
	5	44	23	0.829
	6	47	19	0.698
	7	50	14	0.505

Sample Group	Test No.	Water Temp. (^{0}C)	Weight Loss (mg)	Corrosion Rate (mm/yr)
C (520^{0}C)	1	30	2	0.072
	2	34	6	0.205
	3	37	8	0.288
	4	40	13	0.476
	5	44	20	0.721
	6	47	15	0.557
	7	50	8	0.288
D (560^{0}C)	1	30	4	0.144
	2	34	7	0.251
	3	37	10	0.360
	4	40	15	0.540
	5	44	18	0.649
	6	47	13	0.476
	7	50	5	0.180

Fig. 3 shows combined graph of corrosion rate of samples of all groups. With increasing water temperature the rate of oxidation goes on increasing due to which graph shows an increase in corrosion rate at first.

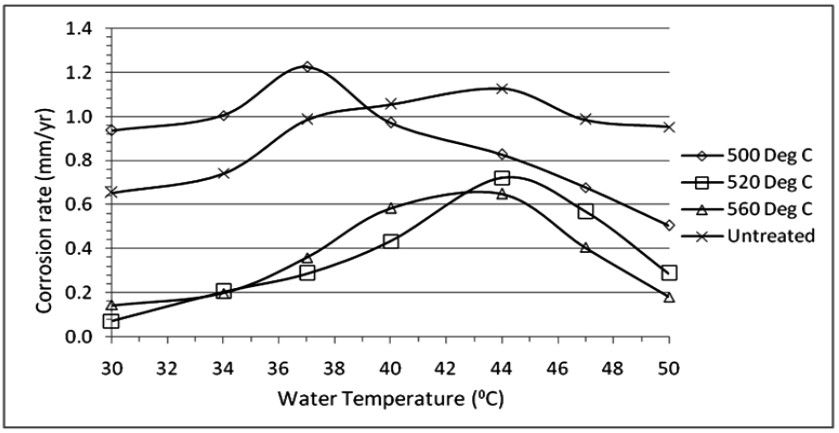
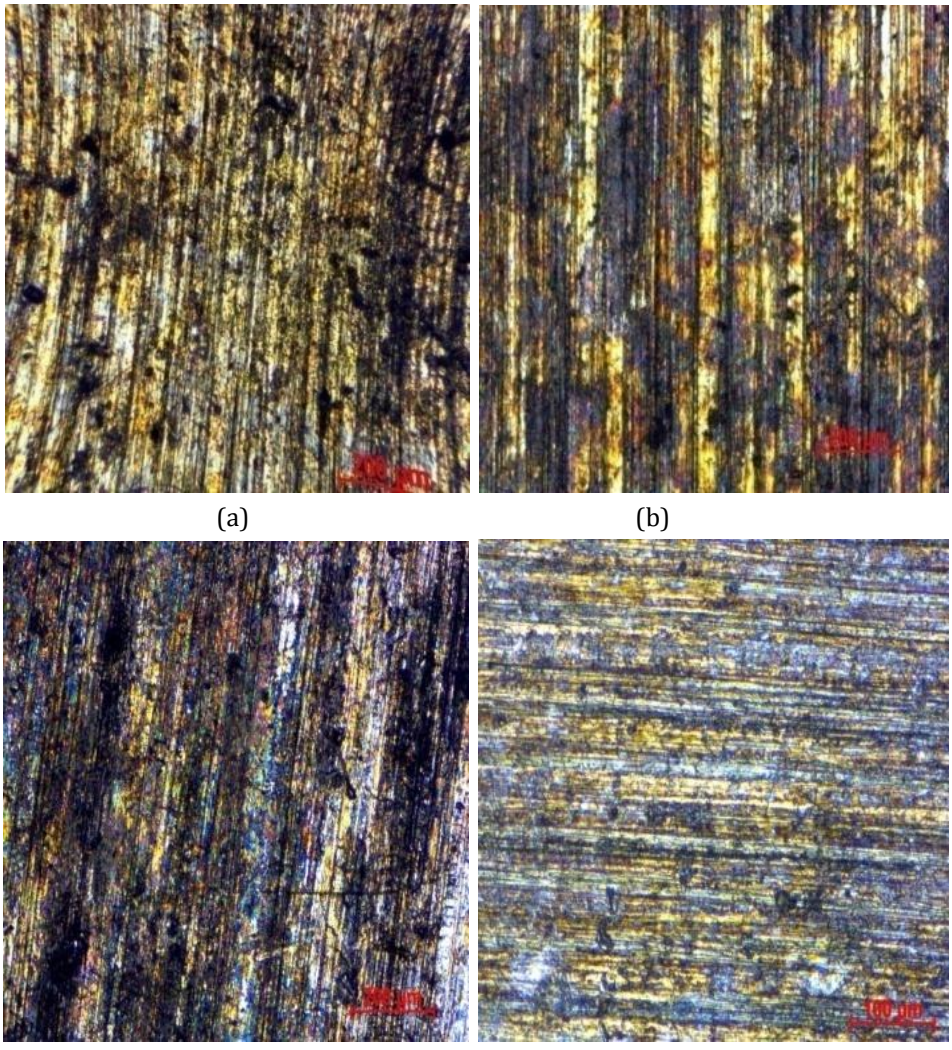


Fig. 3. Graph of corrosion rate vs. water temperature for specimens of untreated alloy and samples precipitation hardened at 500^{0}C, 520^{0}C, 560^{0}C

For corrosion systems, increasing the temperature increases rate of oxidation reaction. However oxide film formation results into passivity. Rate of passive film formation increases with increase in temperature. Also closed experimental set-up causes lack of aeration which results in lack of oxidation required for further corrosion. These two factors are responsible for decreasing the corrosion rate on further increasing the temperature. Fig. 4 shows the microstructures of samples tested in artificial sea water at various temperatures for 72 hours. Black spots on surface shows the pits whereas whitish surface shows passive film formed on material.



(a) (b)

(c) (d)

Fig. 4. Microstructure of sample under corrosion test (a) in water at 30^0C & sample heat treated at 500^0C/12 hrs (b) in water at 30^0C & sample heat treated at 520^0C/12 hrs (c) in water at 37^0C & sample heat treated at 560^0C/12 hrs(d) in water at 50^0C & sample heat treated at 520^0C/12 hrs

Fig. 4 (a) & (b) shows the microstructures of samples; precipitation hardened at 500^0C/12 hrs and 520^0C/12 hrs respectively; under corrosion test in water at 30^0C. Surface of specimen in Fig. 4 (a) shows more number of pits as compared to that on sample shown in Fig. 4 (b). More number of pits results into more weight loss and higher corrosion rate of material. Hence former sample shows more corrosion rate than later one.

Fig. 4 (c) shows microstructure of sample kept in water at 37^0C with prior precipitation hardening at 560^0C/12 hrs. It shows higher pit density with less amount of passive film coating on surface. Fig. 4 (d)

shows microstructure of sample precipitation hardened at 520^{0}C/12 hrs and kept in water at 50^{0}C for corrosion test. Passive film formed on surface of this specimen is higher whereas pit density is very low.

Fig. 4 shows that corrosion rate at intermediate temperature is higher as compared to corrosion rate at room temperature and high temperature (i.e. 50^{0}C).In general; on the samples treated at lower water temperatures (i.e. 30^{0}C to 37^{0}C)pit density as well as pit depth is comparatively less. At intermediate water temperatures (i.e. 40^{0}C to 47^{0}C) pit density on samples is less as compared to that at higher water temperatures however pit depth is more which is the cause of increased weight loss. Samples treated at higher water temperature showed more pits having less depth. Surface under oxide (passive) layer is found to be more in these samples.

Aeration is found to be responsible for this effect. At lower water temperatures initial corrodent attack on surface is less due to less water temperature. It results into low pit density. But with increase in time, pit depth is found to be increasing due to availability of air.

With increase in water temperature attack of corrodent on surface is increased. This leads to more pit density at higher water temperatures. But since aeration is not provided in set-up, with increase in time period air available goes on reducing. Also previously formed oxide layer on surface resists further corrosion. Combined effect of these two causes reduction in corrosion rate.

From optical microstructures shown in Fig. 2 and Fig. 4, it is found that non-uniform microstructure of specimen aged at 500^{0}C leads to its higher corrosion rate. Also it can be seen that for untreated samples the Mg_2Si phase is responsible for the higher corrosion rate. Whereas for specimen aged at 520^{0}C and 560^{0}C corrosion rate is less due to phase change and uniform grain structure.

4. Conclusion

The researches included study of the influence of applied heat treatment on hardness and corrosion resistance of 6082-T6 Al alloy and also provided further information about the resulting microstructures.

- Smaller grain size results into higher hardness values. For all 3 precipitation hardening treatments, it has been found that, artificial aging at 160^{0}C for 12 hours gives highest hardness.
- Grain size, grain structure, composition of alloy; inter-metallic particles and secondary phase particles influences the hardness and corrosion resistance of alloy.
- Considering hardness and corrosion resistance properties optimum heating and aging parameters for 6082-T6 aluminium alloy are 520^{0}C /12hrs and 160^{0}C /12hrs respectively.
- Intensity of pitting attack increases with increase in corrodent temperature from 30^{0}C to 50^{0}C. Lack of aeration affects corrosion rate at higher water temperatures. However, it may not be the case in open sea.
- At lower sea water temperatures (i.e. 30^{0}C to 37^{0}C), alloys precipitation hardened at 520^{0}C as well as 560^{0}C shows good corrosion resistance, indicating their usefulness in marine environment.

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