Key Engineering Materials
ISSN: 1662-9795, Vol. 988, pp 11-20
doi:10.4028/p-sEDG1G

Submitted: 2023-11-21
Revised: 2024-03-11
Accepted: 2024-03-12
Online: 2024-09-27

Simulation of Quench Rate by Jominy End Quench Test for 6082 Aluminium Alloys

Aleyna Gümüşsoy[1,a*], Onur Gülbaba[1,b], Işık Kaya[1,c], Emrah Fahri Özdoğru[1,d]

[1]TRI Metalurji A.Ş., Istanbul, Turkey

[a]aleyna.gumussoy@trimetalurji.com, [b]onur.gulbaba@trimetalurji.com, [c]isik.kaya@trimetalurji.com, [d]emrah.ozdogru@trimetalurji.com

Keywords: EN AW 6082, Jominy End Quench Test, Quench Rate, Quench Sensitivity, Hardness.

Abstract. In the present study, it is aimed to investigate the influence of quench rate on the hardness and electrical conductivity that obtained after artificial aging by using Jominy End Quench test method. The Jominy End Quench test bars were solution heat treated at 560°C for 3 hours. After solution heat treatment, water, spray, and air quenching media were used in order to obtain different quench rates. After the quench, quench rate determination, hardness and electrical conductivity measurements were performed for three different quenching medias. Then, artificial aging heat treatment were applied to all samples at 180°C for 8 hours to understand the effect of quench rate on aging process. The relationship between quench rate, hardness and electrical conductivity have presented.

Introduction

The 6XXX series aluminium alloys are an important subgroup of wrought aluminium alloys and have significant potential in many industrial applications. The most important feature of these alloys is their high strength and good workability properties obtained by the addition of elements such as magnesium and silicon [1]. The mechanical properties of this alloy series can be improved by heat treatment processes known as precipitation hardening. The EN AW 6082 aluminium alloys are particularly popular in structural applications, they are used in the crash boxes for automotive industry and battery trays for EV industry [2].

The heat treatment stages of 6XXX series aluminium alloys basically consist of three stages, solution heat treatment, quenching, and aging. The transformation during these processes is considered as follows, which is generally accepted in the literatures, is: SSSS → atomic clusters → GP zones → β´´→ β´ → β (stable) where SSSS is the super saturated solid solution [3]. Quenching is an important stage in order to achieve the desired mechanical properties after aging. Therefore, it is crucial to determine the appropriate cooling conditions of the alloys in the heat treatment processes of the products in industrial applications.

The Jominy End Quench test is designed to measure the quench sensitivity of an alloy. The test was originally designed to measure the hardenability of steel; on the other hand, it is showed by other researchers that it could be an effect tool for other types of alloys including aluminium alloys. The test accomplishes this task by machining a Jominy bar out of the desired material and quenching the bar from one end giving a range of different cooling rates down the length of the bar. The hardness is then taken along the length of the bar in the axial direction and each measurement is corresponded to a cooling rate from each different section of the bar [4].

In this study, it is aimed to investigate the relationship between quench rate, hardness, and electrical conductivity test results of commercial EN AW 6082 alloy by using the Jominy End Quench test method. The Jominy End Quench test offers a method for studying different quenching conditions with EN AW 6082 samples. The present work identified the effect of quench rate on the hardness and electrical conductivity of EN AW 6082 alloys in water, spray and air quenching medias. The potential for developing a new understanding of aluminium alloys for processing conditions, especially cooling rate, and artificial aging, have presented.

Materials and Methods

Melting and alloying experiments were performed in electric resistance furnace at 750°C, after that the melt was subsequently poured into a steel mould to form Jominy test bar. Chemical composition of the studied EN AW 6082 alloy was measured by HITACHI Foundry-Master Smart optical emission spectrometer and given in Table 1.

Table 1. Chemical composition of the studied EN AW 6082 alloy (wt%)

Elements	Si	Fe	Cu	Mn	Mg	Ti
EN 573-3	0,7 – 1,3	0,50	0,10	0,40 – 1,0	0,6 – 1,2	0,10
Studied Alloy	0,95 - 1,0	0,20 - 0,25	0,05-0,10	0,50 – 0,55	0,60 - 0,65	0,015 - 0,02

The Jominy End Quench specimens were prepared in accordance with ASTM A 255. Fig. 1 shows the Jominy end quench test specimen. 5 mm diameter holes were drilled at 10 and 90 mm for K type thermocouples for the temperature record during quenching. The specimens were placed in furnace and solution heat treated for 3 hours at 560°C.

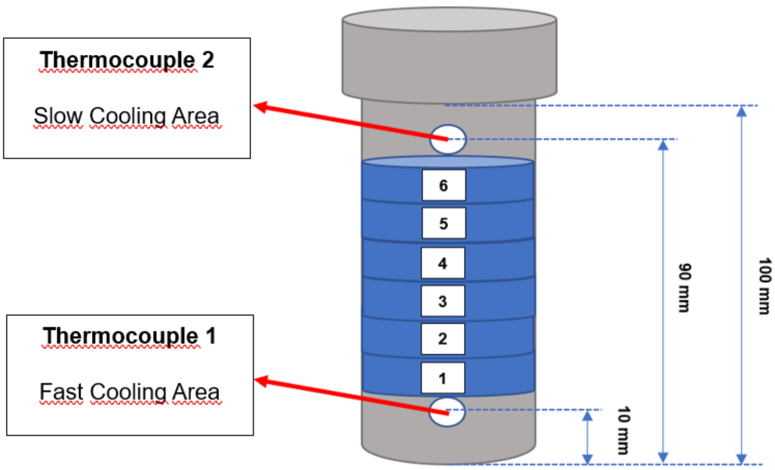


Fig. 1 Jominy End Quench test specimen

The specimen was then removed from the furnace and placed into the Jominy End Quench test rig. Typical transfer time between the furnace door opening and the start of the quench was approximately 10 seconds. Water, spray and air quenching medias were used in order to obtain different quench rates. The nozzle used for quenching is conical shape and spray cone angle is 5°. Tap water is used for water and spray quenching experiments. The spray water pressure initially fixed at 1,5 bar. The specimens remained in the Jominy quench rig for all three water, spray and air quenching experiments for 10 minutes to allow sufficient time to cool to the room temperature. Experimental flow sheet is given in Fig. 2.

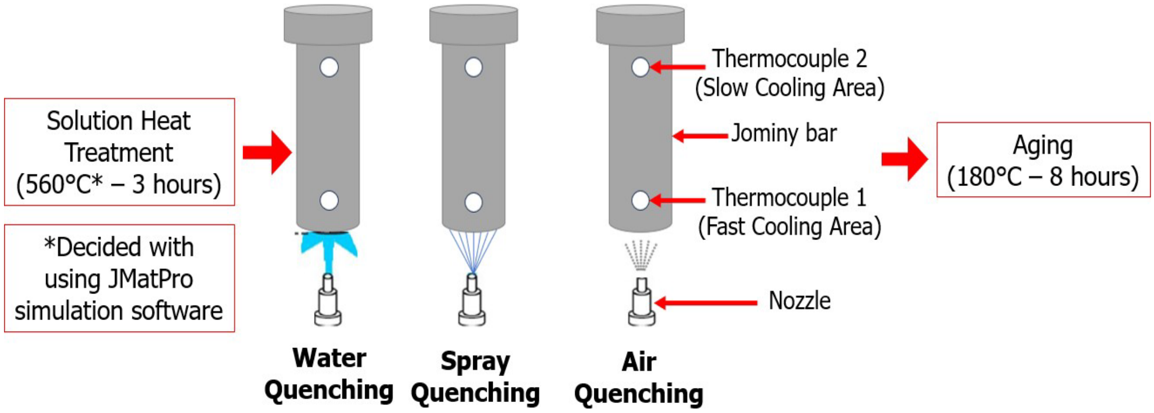


Fig. 2 Experimental flow sheet

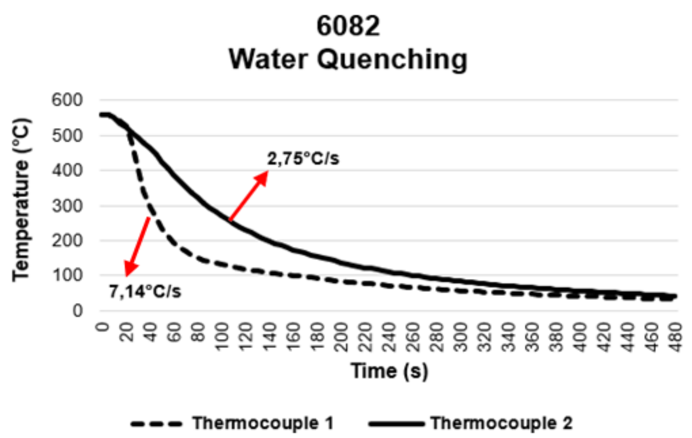
After the specimens has been fully quenched, parallel flats were cut equally on the specimen and hardness and electrical conductivity measurements were performed at the center of the bars. Brinell hardness measurements were applied with DURASCAN 50G5 EMCOTEST and electrical conductivity measurements were performed with Fischer SIGMASCOPE SMP350 device with Fischer FS40 probe for 6 regions as described in Fig. 1.

After the Jominy end quench test, the samples taken from the 1st and 6th regions (1st region: fast cooling area, 6th region: slow cooling area) were grinded, polished, and etched with HF (5%) for metallographic investigation. Microstructural characterization was performed using NIKON LV150N Optical Microscope. Samples were aged at 180°C for 8 hours. After aging heat treatment, hardness and electrical conductivity measurements and microstructure investigations were performed for 1st and 6th regions samples.

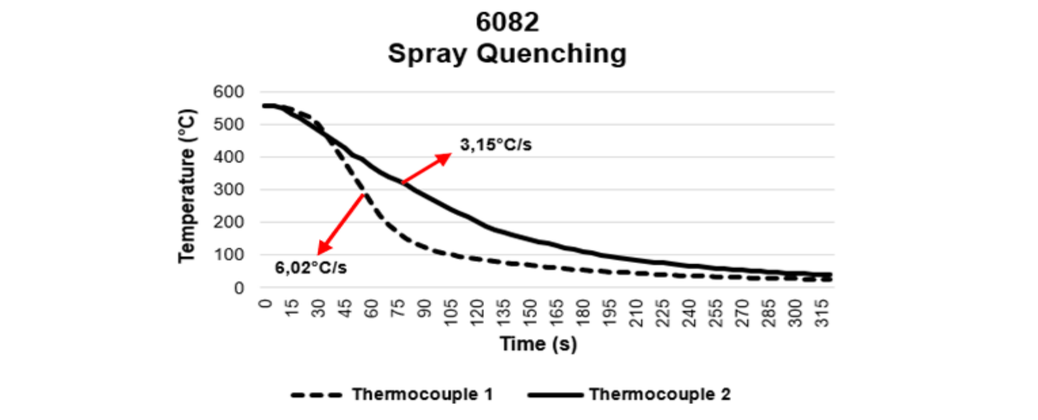
Results and Discussion

Cooling Curves

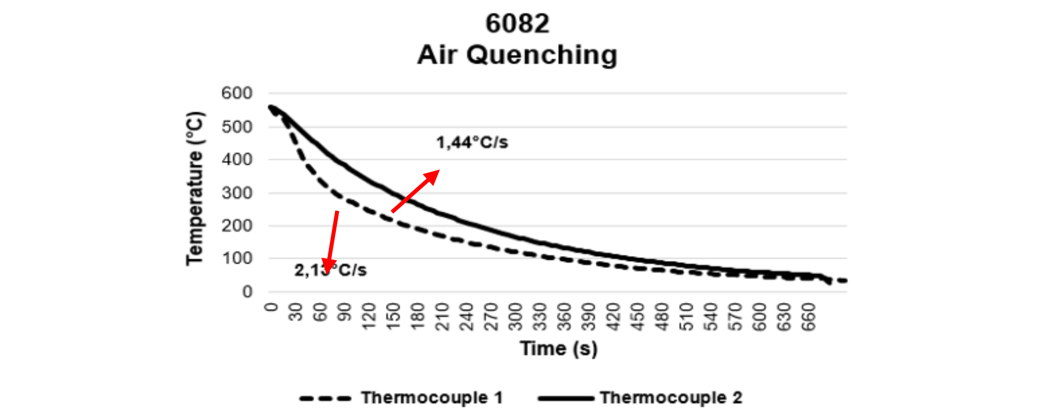
The cooling rates are important to calculate because there is a direct correlation between cooling rate and the mechanical properties after the T6 heat treatment. After the heating and cooling data from fast and slow cooling area were collected, the filtered data was plotted as is to generate a time-temperature curve or cooling curve. The important transformations in these alloys take place while they are being cooled down from 500°C to 200°C through quenching [5]. The average cooling rates were calculated within this temperature range for water quenching (WQ), spray quenching (SQ) and air quenching (AQ) experiments. The cooling curves that obtained from water, spray and air quenched samples were given in Fig. 3.



(a)



(b)



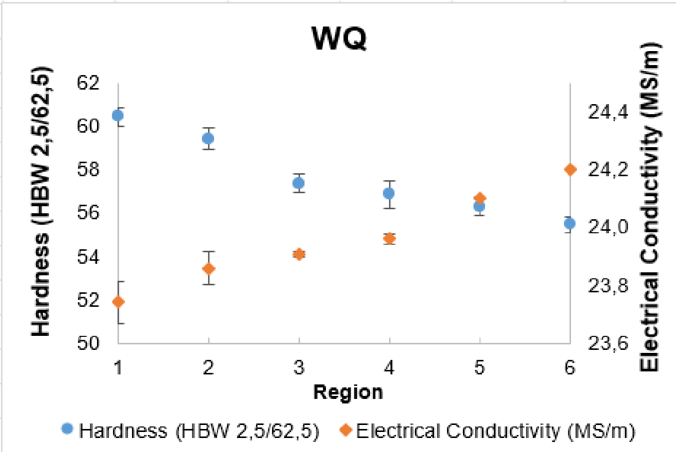
(c)

Fig. 3 Cooling curves **(a)** WQ, **(b)** SQ, **(c)** AQ

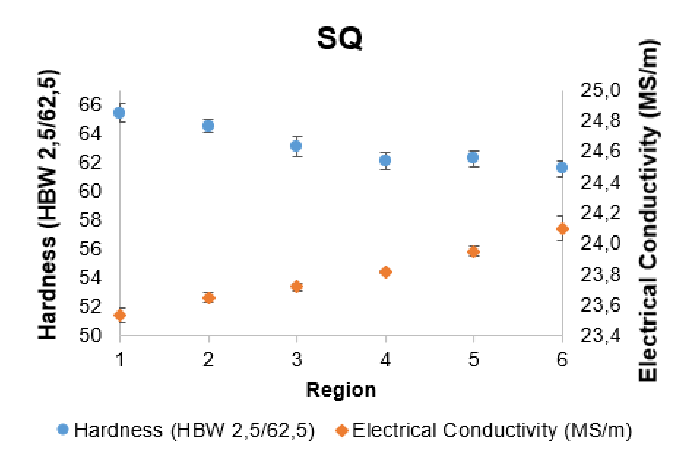
For the fast cooling area, the data shown in Fig. 3 shows extremely fast cooling of the sample for the WQ case (cooling rate of ~7,14°C/s) in contrast the SQ sample had an average cooling rate of 6,02°C/s. The AQ sample was cooled slowest at an average cooling rate of 2,13°C/s. Using these graphs, the cooling rate at any position along the Jominy bar can be obtained and a measured hardness can be correlated to a cooling rate. As shown in Fig. 3, the cooling rates are highest close to the quenched end and rapidly decrease along the length of the bar.

Hardness and Electrical Conductivity Measurements

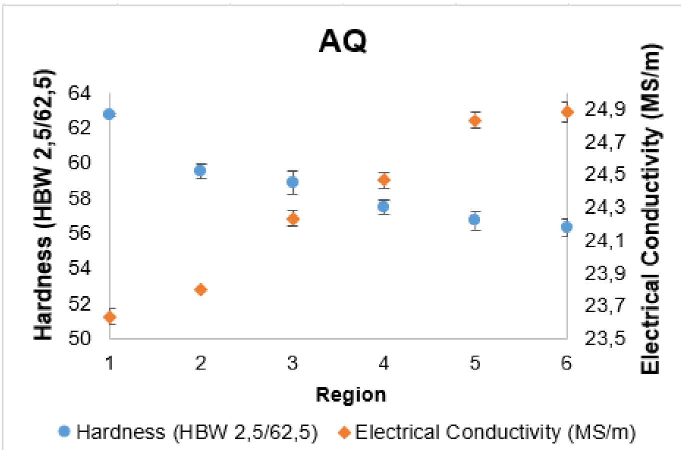
It is well known that hardness and electrical conductivity can be correlated with changing cooling rates. As mentioned in the previous sections, quenching with water was designed to provide the fastest cooling rate. The second quenching procedure was to cool sample with spray water and the third procedure was air quenching. Fig. 4 shows the results of the hardness and electrical conductivity plotted against the three different average cooling rates.



(a)



(b)

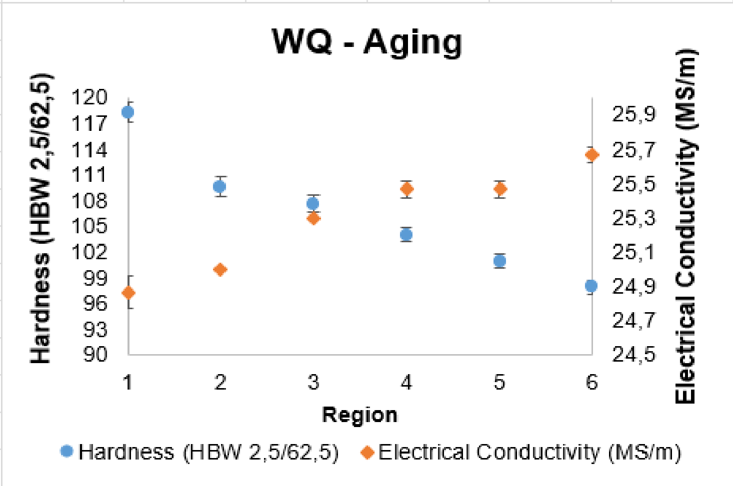


(c)

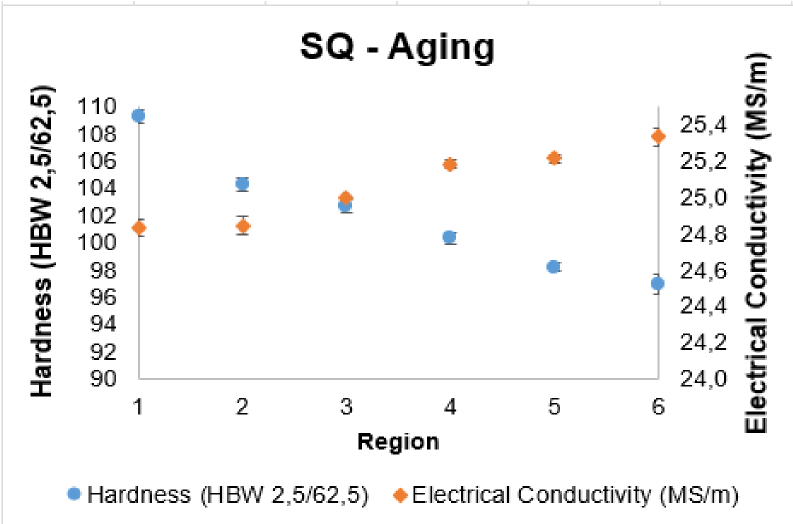
Fig. 4 Hardness and electrical conductivity test results after Jominy End Quench Test **(a)** WQ, **(b)** SQ, **(c)** AQ

From Fig. 4, for all three conditions, it can be clearly seen that that the hardness decreased with decreasing cooling rates while the electrical conductivity increases. This is probably because of the precipitation of non hardening precipitates during slow cooling. Birol (2016) explained that the fractions precipitated during cooling are estimated from electrical conductivity measurements [6]. This is evidenced by the electrical conductivity values that increase with decreasing cooling rates.

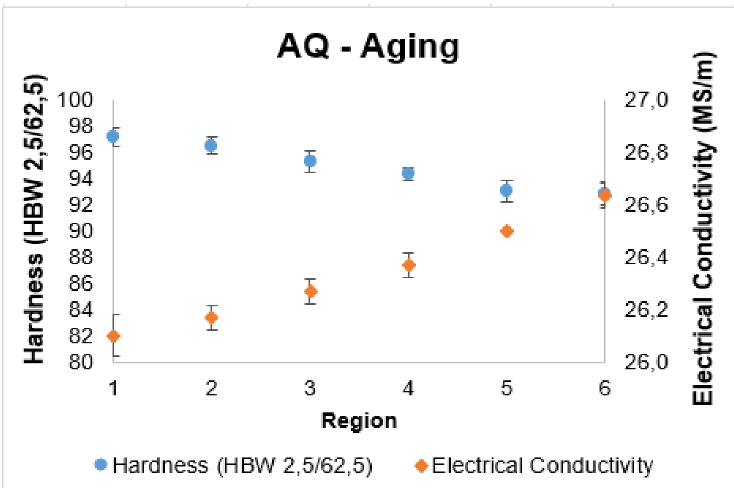
The cooling rate can play a major role in the overall mechanical properties of the alloy [7]. To see the effect of quench rate on mechanical properties after aging, the samples were artificially aged at 180ºC for 8 hours. The results are given in Fig. 5.



(a)



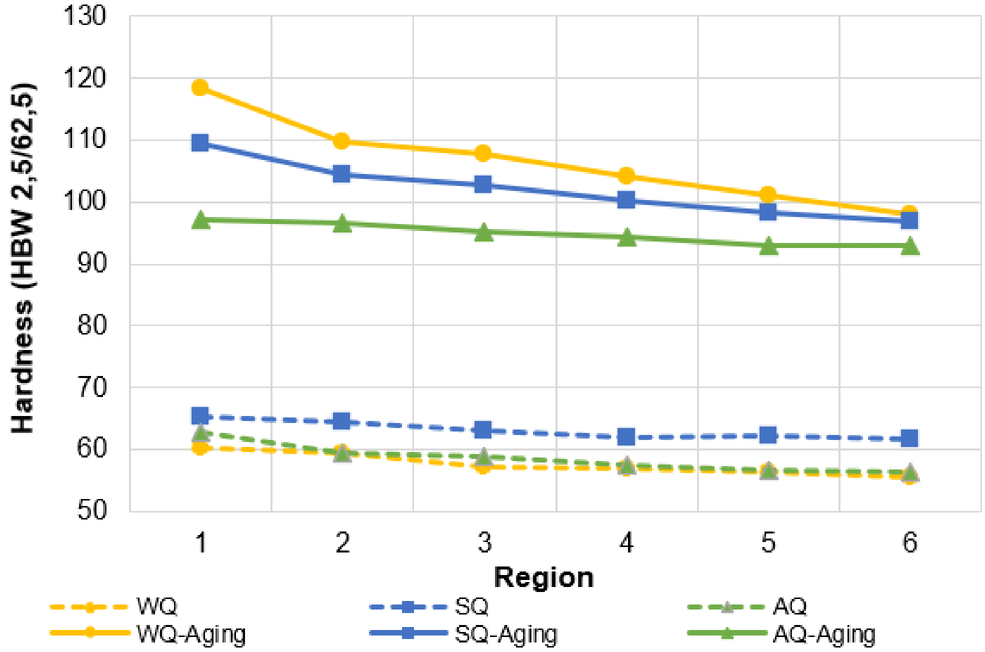
(b)



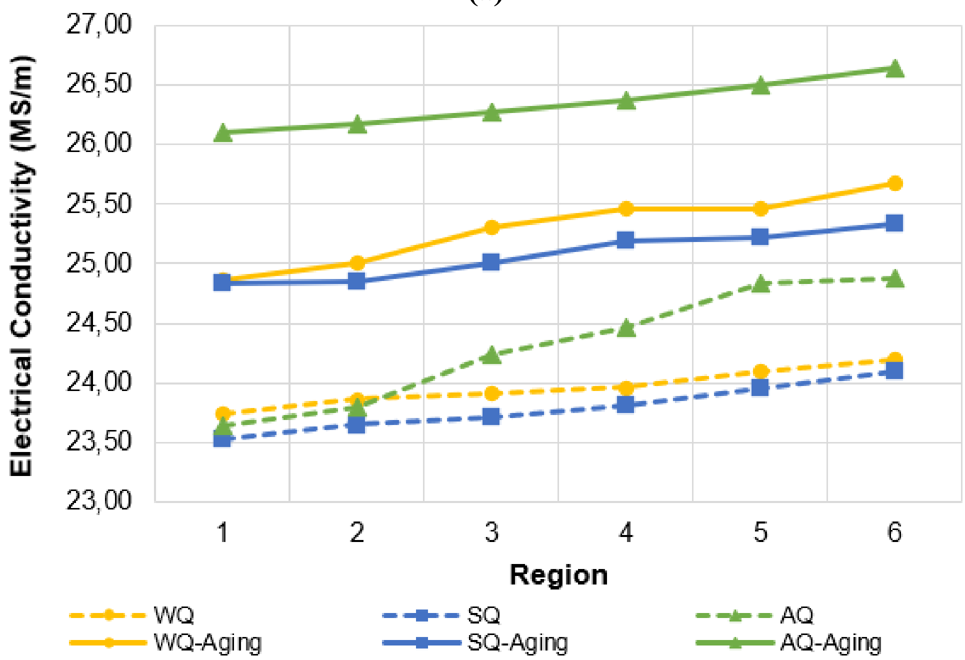
(c)

Fig. 5 Hardness and electrical conductivity test results after aging at 180°C for 8 hours **(a)** WQ, **(b)** SQ, **(c)** AQ

After the T6 heat treatment, WQ-fast cooled sample reached the highest hardness value as 120 HBW due to the highest cooling rate (Fig. 5a) while the AQ-slow cooled sample reached the lowest hardness value as 93 HBW (Fig. 5c). This is because when the cooling rate is too low, due to the growth of the coarse β-Mg_2Si phase, the degree of supersaturation of solid solution is reduced and resulting in the reduction of the mechanical properties after aging [7]. Comparative hardness and electrical conductivity results of as-quenched and aged samples are given in Fig. 6.



(a)



(b)

Fig. 6 Hardness and electrical conductivity results of all experiments **(a)** hardness **(b)** electrical conductivity

From Fig. 6a, it can be observed that the alloy appear to be very quench sensitive between Region 1 and Region 6 due to the decreasing cooling rate for WQ and SQ experiments. On the other hand, in the AQ experiments, the cooling rate variation between Region 1 and Region 6 is quite low as 2,13°C to 1,44°C/s. For this reason, no significant difference was observed in the hardness values of the AQ sample. From Fig. 6b, as expected, AQ samples reached the highest electrical conductivity results due to the slow cooling rates.

Microstructural Analysis

After aging at 180°C for 8 hours, samples of interest were prepared using the metallographic sample preparation procedure. Six of the water, spray and air quenched samples which are represents the fast and slow cooling area were prepared for the metallographic examination. Fig. 7 shows the microstructures of fast and slow cooling areas after aging.

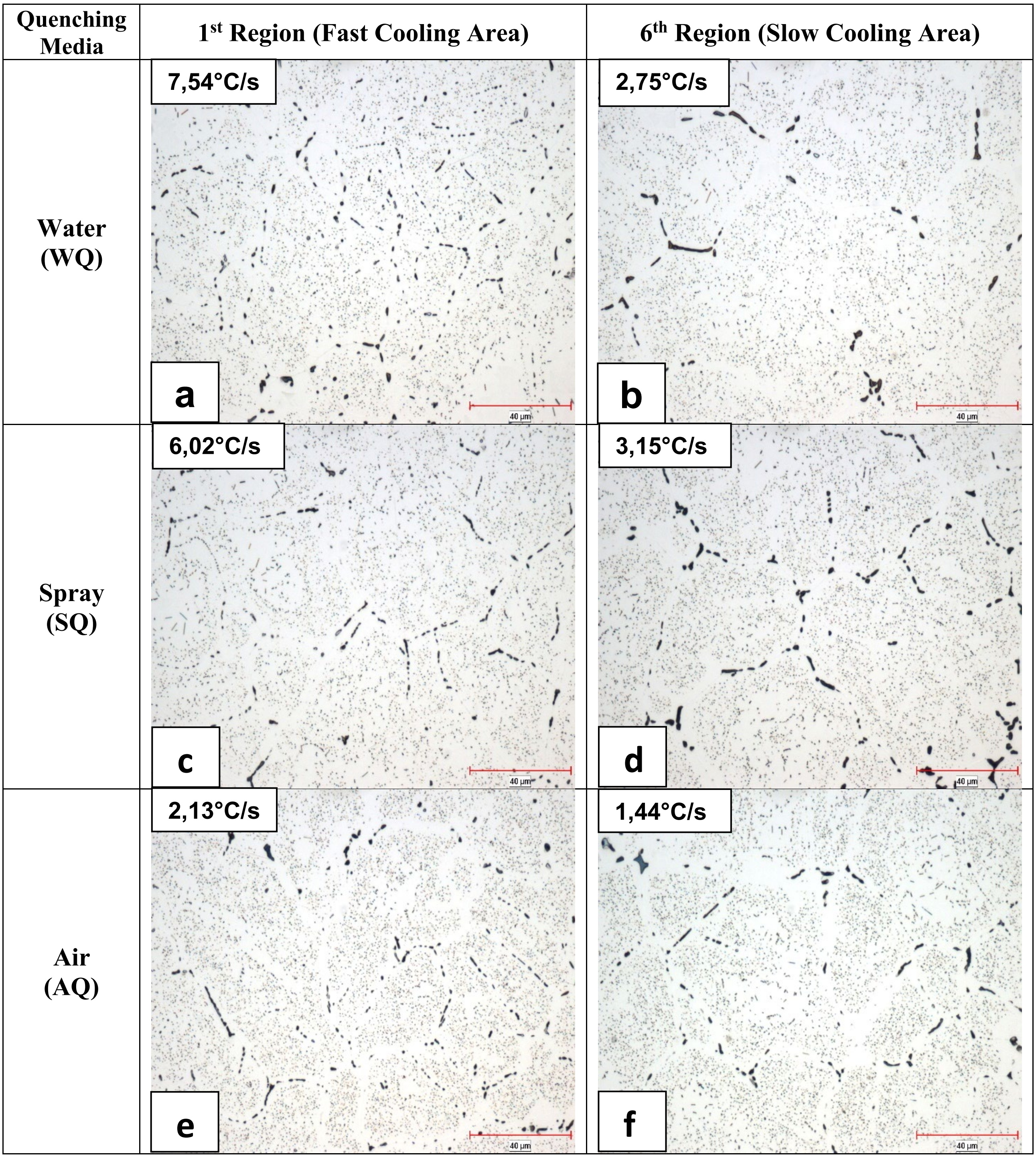


Fig. 7 Microstructures of the samples after aging **(a)** WQ-fast cooling area, **(b)** WQ-slow cooling area, **(c)** SQ-fast cooling area, **(d)** SQ-slow cooling area, **(e)** AQ-fast cooling area, **(f)** AQ-slow cooling area

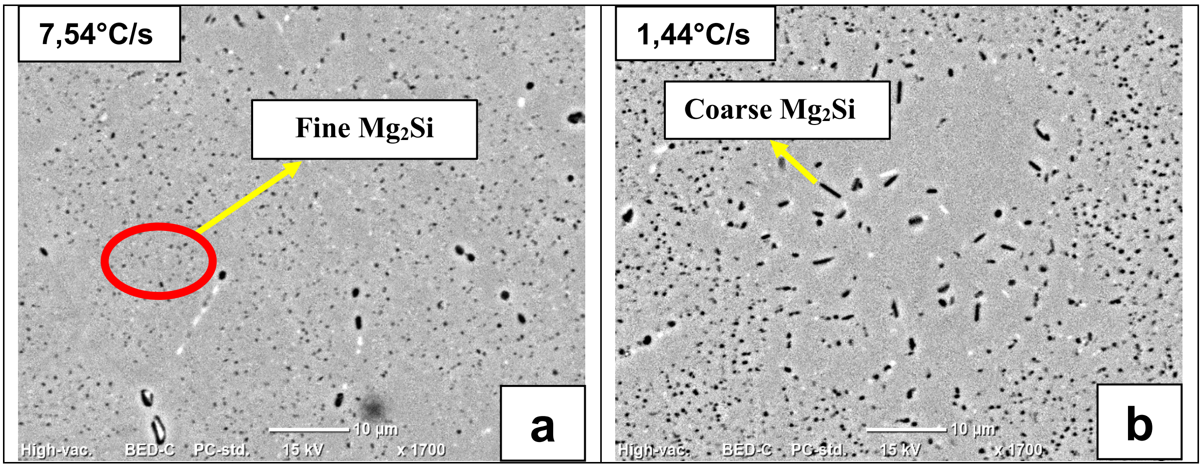


Fig. 8 SEM images of the samples after aging **(a)** WQ-fast cooling area (7,54°C/s), **(b)** AQ-slow cooling area (1,44°C/s)

Depending on optical microscopy and SEM examinations, it can be observed that as the cooling rate decreases, the number of coarse precipitates increase (Fig. 7 and Fig. 8). As discussed in the previous section, when the cooling rate is too low the hardness decreases. The main reason is slow cooling tends to produce coarse Mg_2Si phases (Fig. 8b).

And with decreasing cooling rate, precipitate free zones are more intensely. Slow cooling results in a higher number of grain boundary precipitates and a wider precipitate free zone (PFZ) [9]. In Figure 7b, for the AQ-slow cooled sample, precipitate free zones are more intense and larger in comparison with WQ-fast cooled sample (Fig. 7a).

Conclusion

On the basis of investigation results presented above, the following conclusions can be drawn:

The cooling rate decreases with distance from the quenching end. Water quenching provides the highest quench rate.

With decreasing cooling rate, the hardness values of the alloy decrease while the electrical conductivity increases. After T6 heat treatment, WQ-fast cooled sample reached the highest hardness value due to the highest cooling rate (120 HBW).

The reduction in the mechanical properties was attributed to the loss of solute atoms which precipitates as coarse precipitates during slow cooling. This is because at slower quench rates, the dispersoid phases are able to act as nucleation sites for coarse Mg_2Si precipitates.

With decreasing cooling rates, precipitate free zones (PFZs) can be observed more intensely.

References

[1] W.S. Miller, L Zhuang, J Bottema, A.J Wittebrood, P De Smet, A Haszler, A Vieregge, Recent development in aluminium alloys for the automotive industry, Materials Science and Engineering: A, 280(1) (2000), 37–49.

[2] A. Güzel, A. Jäger, N. Ben Khalifa, A. E. Tekkaya, Simulation of the Quench Sensitivity of the Aluminum Alloy 6082, 424 (2010), 37-49

[3] C. D. Marioara, S. J. Andersen, J. Jansen, H. W. Zandbergen,). Atomic model for GP-zones in a 6082 Al–Mg–Si system, Acta Materialia, 49(2) (2001), 321-328.

[4] G.P. Dolan, R.J. Flynn, D.A. Tanner, J.S. Robinson, Quench factor analysis of aluminium alloys using the Jominy end quench technique. Materials Science and Technology, 21(6) (2005), 687–692.

[5] A. Assaad, Quench Sensitivity of 6xxx Aluminum Alloys, Master's Thesis, University of Waterloo (2016).

[6] Y. Birol, Effect of cooling rate on precipitation during homogenization cooling in an excess silicon AlMgSi alloy. Materials characterization, 73 (2012), 37-42.

[7] H.Y. Li, C.T. Zeng, M.S. Han, J.J. Liu, X.C. Lu, Time–temperature–property curves for quench sensitivity of 6063 aluminum alloy. Transactions of Nonferrous Metals Society of China, 23(1) (2013), 38–45.

[8] T. Saito, C.D. Marioara, J. Royset, K. Marthinsen, R. Holmestad, The effects of quench rate and pre-deformation on precipitation hardening in Al–Mg–Si alloys with different Cu amounts. Materials Science and Engineering: A, 609 (2014), 72–79.