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Effects of different heat treatment methods on the mechanical properties and structures of Al-6061

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ABSTRACT
The Al 6061 alloy is mainly hardened by the precipitation of the secondary Mg_2Si and ternary (Al-Mg-Si) eutectic. In this work, the Al 6061 plates have been heat-treated by four different methods and thereafter the tensile strength, hardness and microstructural attributes have been compared. The first plate was kept untreated or in 'as received' condition. The remaining four samples were solution annealed (SA) at 350°C for 1.5 h of soaking time. The SA was followed by (1) only water quenching (WQ) in the 2nd sample; (2) water quenching + ageing (WQ + Ag) in the 3rd sample; (3) only furnace cooling (FC) in the 4th sample, and (4) furnace cooling + ageing (FC + Ag) in the 5th sample. The ageing was performed at 150°C for 4 h of holding period. The study revealed that WQ increases the ductile behaviour of the Al 6061 alloy but with a loss of ultimate tensile strength (UTS) and yield strength (YS). The WQ + Ag sample showed an improvement of 23% in elongation, while the FC sample had the lowest UTS and YS. The WQ + Ag sample showed a slight improvement in UTS and YS, while the FC + Ag sample recovered UTS, YS, and hardness, which were dropped during plain FC.

L'Al 6061 comprend principalement les éléments d'alliage Mg et Si. Cette nuance est très utilisée dans des industries variées en raison de sa nature traitable thermiquement et de ses propriétés de résistance à la corrosion. Pendant le traitement thermique, l'alliage d'aluminium est initialement recuit pour former une solution solide uniforme sans contraintes internes. L'alliage chauffé est ensuite trempé pour stabiliser les éléments d'alliage à la température ambiante. La troisième étape est le vieillissement de l'alliage à une température relativement basse pour produire des précipités des éléments constitutifs. L'alliage est endurci principalement par précipitation de Mg_2Si secondaire et d'eutectique ternaire (Al-Mg-Si). Dans ce travail, on a traité thermiquement les tôles d'Al 6061 par quatre méthodes différentes et ensuite, on a comparé la résistance à la traction, la dureté et les attributs microstructuraux. On a conservé la première tôle non traitée ou dans un état «tel que reçu». On a appliqué aux quatre échantillons restants un traitement de mise en solution (SA) à 350°C pendant 1.5 heure de trempage. Le SA était suivi par (1) une trempe à l'eau (WQ) uniquement dans le 2^e échantillon; (2) une trempe à l'eau + un vieillissement (WQ + Ag) dans le 3^e échantillon; (3) un refroidissement au four (FC) uniquement dans le 4^e échantillon; et (4) un refroidissement au four + un vieillissement (FC + Ag) dans le 5^e échantillon. On a réalisé le vieillissement à 150°C pendant une période de maintien de 4 heures. L'étude a révélé que WQ augmente le comportement ductile de l'alliage Al 6061, mais avec une perte de la résistance ultime à la traction (UTS) et de la limite d'élasticité (YS). L'échantillon WQ +Ag a montré une amélioration de 23% de l'allongement, tandis que l'échantillon FC avait l'UTS et l'YS les plus faibles. L'échantillon WQ + Ag a montré une légère amélioration de l'UTS et de l'YS, tandis que l'échantillon FC + Ag récupère l'UTS, l'YS et la dureté, qui ont été abaissées lors du simple FC.

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KEYWORDS
Al 6061; ageing; furnace cooling; heat treatment; mechanical properties; water quenching

Introduction

Heat treatment is possible with the 6XXX series alloy. Because 6061 aluminium contains silicon and magnesium, it may be heat treated to increase its strength. When fully soft and annealed, it has good formability, and after heat treatment, the strength may be greatly improved. The Al-Mg-Si medium-strength alloys have exceptional corrosion resistance. They are mostly strengthened by the ageing precipitate Mg_2Si. Additional silicon is added to other alloys to strengthen them, but improper heat treatments might make the additional silicon alloys more susceptible to 'stress

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corrosion cracking (SCC)' [1]. Al 6061 alloys are often utilised in various parts of ships, motorboats, aeroplanes, automobile bodies, rail coaches, etc [2]. To improve their mechanical qualities, the heat-treatable Al-alloys undergo solution annealing, quenching, and ageing. To get the greatest solution of the components, performing a solution heat treatment at near liquidus temperature is feasible. To dissolve soluble components and produce a solid solution, the alloy is heated to a high temperature. The selection of the maximum solution temperature varies according to the alloy although it typically ranges from 300 to 500°C. A hard outer shell is formed by quenching the alloy. The most popular quenching medium is water; however, the cooling rate may be adjusted using additions. Aqueous solutions of poly-alkalene glycol, boiling water, water heated to 65–80°C and forced air blast, are among the quenchants utilised in slower quenching applications. Either room temperature (natural ageing) or a precipitation heat treatment (artificial ageing) is used to accomplish hardness following solution treatment and quenching. To extract dissolved components, the alloy is aged for a longer duration at a lower temperature. This eliminates undesirable qualities and can be used to attain the required level of ductility and strength [3–5]. In previous research works, different types of variations have been done in the quenching media as well as in the alloying elements of the Mg-Si-based Al-alloys. Some of the relevant works performed on Al 6061 alloy are summarised here:

Beder et al. analysed the cast $AlSi_{10}Mg$ alloy's microstructure, hardness, tensile strength, and dry wear characteristics. The alloy underwent air cooling, quenching, and T6 treatment after being created using gravity die casting. With the T6 treatment, the microstructure changed to a spherical shape, resulting in β-Mg_2Si precipitates and Si particle spheroidisation. Wear resistance, tensile strength, and yield strength all rose by up to 70% after ageing [6]. Xia et al. studied how the mechanical characteristics and microstructure development of Al 6082 aluminium alloy were affected by deep cryogenic-ageing treatment (DCAT), artificial ageing treatment (AAT), and solid solution treatment (SST). According to the results, SST specimens exhibited the highest elongation, in-plane anisotropy, and lowest yield strengths. AAT specimens decreased maximum elongation and IPA while increasing yield strengths. The strongest dislocation pinning effect was seen in DCAT alloys, which led to increased yield strength [7]. Following the addition of Mn and subsequent heat treatment, the microstructure was investigated into the Al-Si–Mg alloy. The findings revealed a Mg-rich Al5Si3Mg2 phase and Mn-rich Al15Mn3Si2 phase. Melting temperatures, fusion enthalpy, and specific heat Cpl were measured, and heat treatment improved hardness and tensile strength. In both heat-treated and non-heat-treated samples, Mn improved electrical resistance [8]. Lu et al. investigated how heat treatment techniques and Hot Forming-Quenching (HFQ) influenced the mechanical properties of AA6016 sheets. According to the results, high-temperature pre-straining (HT-PS) increased the sheet's strength performance, but only modestly at 3% and 7%. Differential scanning calorimetry revealed that HT-PS increased the precipitation of the β″ phase [9]. Aluminium alloys that have been quenched lose some of their surplus vacancies to vacancy sinks and preserve some of them as excess. Compared to fast cooling, slow cooling results in fewer excess vacancies. Although hardening rates only vary in the initial stage, natural ageing (NA) in Al-Mg-Si alloys is essential, indicating that interactions between vacancies and early-stage solute clusters aid in balancing free vacancy fractions [10]. The mechanical characteristics of the Al 6082 alloy components following T6 heat treatment were investigated by Jiang et al. According to the results, yield strength, ultimate tensile strength, and elongation all increase with increasing solution temperature, length, and ageing time. Al(FeMn)Si and β-Mg_2Si are examples of small precipitates that improve mechanical characteristics [11]. The effect of stannum (Sn) addition and solution treatment temperature on the microstructure and hardness behaviour of the Al-0.4Mg-1.0Si alloy was investigated. After quenching treatment, the results indicate that Sn-rich particles remain in the Al matrix, lowering the Mg content. Cluster formation of Mg and Si is delayed due to enhanced natural ageing (NA) suppression caused by higher Sn content and solution treatment temperature. During the early stages of NA, Si-rich clusters form preferentially, whereas Mg-Si co-clusters develop later [12]. The mechanical characteristics of an as-cast aluminium-matrix composite (AMC) with an in-situ-formed Mg_2Si phase were investigated by Zamani et al. [13]. The findings demonstrated that the eutectic Mg_2Si phase and primary particle edges are greatly improved by homogenisation heat treatment, leading to a 44% improvement in UTS and a 335% increase in total elongation to failure. In comparison to previous aluminium-based composites, the extruded sample exhibits superior characteristics, and the composite also demonstrates superior tensile toughness.

Apart from the Al 6XXX series, other series like Al 2XXX and Al 7XXX have also been explored for their mechanical property enhancement after the heat treatment. Al 2XXX series mainly consists of Al-Cu-Mg, whereas the Al 7XXX series comprises Al-Zn-Mg as the main constituents.

Patel et al. analysed the effect of solution heat treatments on Al–3.39% Cu–2.26%Mg alloy's microstructure, thermal, mechanical, and corrosion characteristics. Gravity die casting has been used to create the alloy from 5754 and Al–Cu alloys. The alloy has a Brinell hardness of 77.2 HB and exhibits precipitate phases in its microstructure. Age and heat treatment cause the Brinell hardness to drop to 63.6 HB. Precipitate phase dissolution enhances corrosion resistance. Heat treatment raises the alloy's peak compressive stress [14]. Amin et al. focuses on how the mechanical characteristics of AA2024 are affected by cooling speeds and precipitation hardening. Precipitation hardening at 180°C for one hour increased the UTS by 28.7%, according to the results, which also demonstrate increases in strength and hardness [15]. The hardness and corrosion resistance of Al 2014, a high-strength aluminium alloy used in automotive and aerospace, are examined in relation to three heat treatment procedures. Polarisation investigations demonstrated that the corrosion potential is shifted in a more noble direction by heat treatment, which results in precipitation hardening. Because of the production of stable precipitates, the T6 standard ageing method offered the best hardness and corrosion resistance. While the modified RRA with high-temperature pre-ageing produced poorer performance, the RRA method demonstrated good performance. The results highlight how crucial heat treatment is for enhancing the durability of the Al 2014 alloy [16]. Gangal and Devendra focused on how ageing and time affect the mechanical characteristics of the alloy Al18Si3.6-Cu0.34Ce. After undergoing T6 heat treatment for varied lengths of time, the alloy's shape and spheroidisation changed. The findings demonstrated that ageing increased the as-cast alloy's yield strength and ultimate tensile strength. Additionally, flow stress improved with age, mostly as a result of homogeneity. Along with enhanced load bearing and shear strength with ageing, the study also discovered increases in wear resistance [17]. Using transmission electron microscopy and Vickers hardness tests, the age hardening and precipitation behaviour of the Al-Zn-Mg alloy were investigated. In artificial ageing (AA), precipitation behaviour is influenced by precipitates such as solute clusters and GP zones that occur during natural ageing. Temperature and NA duration have an impact. Hardness is increased with higher AA temperatures, but they also take longer. The study offers recommendations for the 7003 alloy and related aluminium alloy production process [18].

In aluminium alloys in the 7XXX category alloy, Yao et al. investigates how cooling rates affect the composition of quench-induced grain boundary precipitates. It focuses on the η-phase precipitates that nucleate heterogeneously on grain boundaries and are associated with the quench sensitivity of the alloys [19]. Altuntaş and Bostan looked at applying cryogenic treatment to aluminium alloys from the 7XXX series, which are frequently used in space and aviation, following re-ageing and retrogression procedures. The alloy was cryogenically treated, solution heated, and artificially aged. The findings demonstrated that the −40 cryogenic treatment sample had activation energy 50% lower than the non-cryogenic treatment sample, suggesting that the η′ phase formed more readily. According to the study's findings, cryogenic therapy is a useful therapeutic approach [20]. Using cladding quenching, Liu et al. examine how quenching residual stress affects the precipitation behaviour of slabs of the Al 7085 alloy. According to the results, residual stress decreases as cladding layer thickness increases; residual stress is nearly eliminated at a thickness of 1–1.4 mm. The mechanisms underlying the impact of quenching residual stress on the precipitation of 7085 Al alloy are also investigated in this work [21]. Heat treatments' effects on the intrinsic anisotropy of Al 7075 deposits made by cold spray additive manufacturing (CSAM) were examined by Ren et al. [22]. The findings indicate that secondary phases develop and nucleate preferentially at feeding powder particle-particle contacts. Recovery and recrystallisation take place following heat treatments; however, microstructural anisotropy persists. Heat treatment can reduce mechanical anisotropy, but it cannot eradicate it. Microhardness and UTS were highest in the T6 sample. Elongation was greatly enhanced by the sintering process [22]. The effects of ageing treatment and quenching rate on the microstructure and characteristics of Al-Zn-Mg alloys were investigated. Al 7046 After being quenched in water and air, an alloy was aged for 0–120 h at 120°C. The findings indicate that over-ageing treatment has less of an impact on precipitates and precipitation-free zones than the quenching rate. Over-ageing broadens grain boundary PFZs, improving corrosion resistance in water-quenched alloys but harming air-quenched alloys. Tensile and hardness characteristics are not significantly impacted by prolonged over-ageing [23]. The strengthening of the Al 7005 alloy by extreme plastic deformation and ageing treatments was examined in work, with particular attention to artificial ageing prior to distortion and natural ageing following deformation. Due primarily to enhanced precipitate volume percentage, dislocation density, and grain refinement, the results demonstrate outstanding strengthening, with yield strength rising to over 400 MPa. The strength of the alloy may be significantly influenced by the volume proportion of precipitates during natural ageing, according to the study [24]. Several ageing techniques, including as hot extrusion, solid solution, and artificial ageing, were applied to the Al 7A99 alloy. Analysis of the precipitation behaviour and microstructure evolution showed that heat extrusion refined the coarse $Mg(Zn, Cu)_2$ phases. The coarsening and separation of grain boundary precipitations in the over-aged sample resulted in improved corrosion resistance. A series of solid solutions, GPI zones, metastable η′, and stable η were the stages of the ageing process [25]. With an emphasis on the η-phase precipitates that nucleate diversely on grain boundaries and are associated with the quench response of aluminium alloys in the 7xxx series, Yao et al. investigated the effects of cooling rates on the composition of quench-induced grain boundary precipitates [19]. Gao et al. looked at how the microstructure and characteristics of Al 7050 alloy wires were affected by the rates of heating and cooling. The findings indicated that air cooling produced low η′ strengthening phases, but quick heating produced smaller, more uniform grain sizes. However, more solute atoms and nucleation sites were made available by water quenching, which led to more η′ strengthening phases and increased strength [26].

The standard procedure of heat treatment, i.e. solution annealing + quenching + ageing, has been followed for a long time to improve the properties of heat-treatable Al-alloys. The present work analyses the properties of the Al6061 alloy after (a) only quenching; (b) only slow cooling; (c) both quenching + ageing; (d) both slow cooling + ageing. The quenching has been done in water as suggested by various previous research work. For slow cooling, a closed chamber furnace was utilised. Hence, the effect of slow cooling and ageing has been assessed in the light of untreated samples as well as quenched & aged samples.

Materials and methodology

Five plates of the Al 6061 alloy have been considered in this study. Each plate has a uniform dimension, 120 × 75 × 10 mm, and in hot-rolled conditions. The plates were collected from an ISO-certified industry. The EDS analysis has been done to check the amount (weight%) of constituents' elements in the Al 6061 alloy. The EDS mapping images with element Wt% are shown in Figure 1. The first plate has been kept as it is, which means no heat treatment was done on this plate. The remaining four plates (2nd, 3rd, 4th, and 5th) were undergone the same heating condition under an induction furnace. It was a closed chamber furnace, yet there was no vacuum inside the furnace during heating. The heating was done at a constant temperature of 350°C for a common holding time of 1.5 h. The 2nd plate was removed and quenched in water. The 3rd plate was also quenched in water followed by an aging process. The ageing process includes again heating the quenched sample in the furnace at a constant temperature of 150°C for four hours. After four hours of heating, the induction furnace was switched off and this sample was allowed to cool inside the furnace. Hence, it took around 30 h to get cooled to room temperature. The 4th and 5th plates were not taken out from the furnace and they were cooled inside the furnace. After cooling to room temperature, the 4th sample was collected in a 'furnace cooled' state. The 5th sample is also in furnace-cooled state, but it has again undergone into similar ageing process as the third sample . The complete experimental procedure is explained in Figure 2. The physical condition and sample naming are listed in Table 1.

For analysing the effect of quenching and ageing on the mechanical properties of Al plates, the tensile, bending and hardness tests have been carried out in the study. The tensile test specimen has been cut off from each plate. The specimen has been prepared as per the ASTM-E8 standard. The length of the grip and gauge sections of the tensile specimens are 30 and 25 mm, respectively. The tensile test was carried out in the 'FIE Make Universal Testing Machine (UTES 40 HGFL)' of 40 kN capacity. The strain rate of 0.01 s^{-1} was used during the tensile test. The tensile test lasted till the fracture of all the specimens. The hardness of all the plates was tested using a Rockwell hardness tester in B-scale. A total of five locations were indented during the hardness test and an average value of hardness was measured for each plate. To analyse the microstructural attributes of all the plates, optical microscopy was utilised. The microscopic images were captured in two magnifications: i.e. 200x and 500x. For this purpose, small-sized samples of 10 × 10 × 5 mm were cut from each plate. The square cross-sectional part (10 × 10 mm) of the samples was properly polished with the help of various grades of abrasive papers. Keller's reagent was used as an etchant for the polished surface of all the samples. In addition, the XRD analysis was carried out to check any possible oxide peaks that might have been generated during heating or quenching. The specimen size for the XRD analysis was 15 × 10 × 5 mm. The XRD peaks were obtained within a diffraction angle (2θ) of 20°–90°. The specimens used for the tensile test are shown in Figure 3.

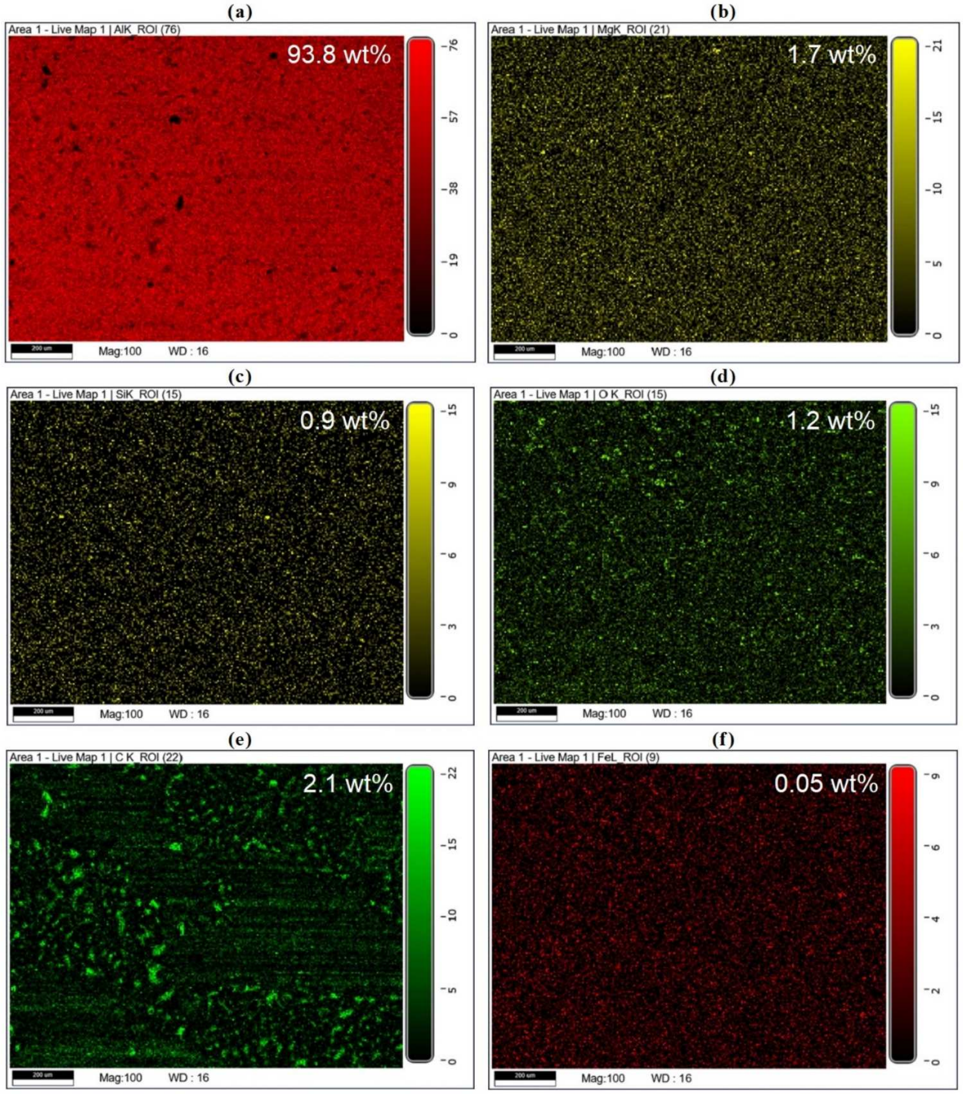

Figure 1. EDS mapping of the Al 6061 alloy showing the weight % of various constituents' elements: (a) Al; (b) Mg; (c) Si; (d) O; (e) C; and (f) Fe.

Result analysis

Tensile test

The tensile test was concluded by obtaining a graph between stress vs strain. All five specimens have been fractured through the reduced cross area (at the mid-part of gauge length). The fractured specimens are shown in Figure 4(a). A comparative graph has been plotted comprising the tensile test data of all the samples (Figure 4(b)).

Sample 1 (AR) has shown a UTS of 127.9 MPa after a maximum load of 8 kN was applied. Just below the maximum load value, the yield point reached at 7.34 kN of load application. The yield stress (YS) of 116.8 MPa was recorded for the AR sample. The maximum displacement of 11.9 mm was recorded in the sample till fracture. In sample 2, the UTS (123 MPa) and YS (106 MPa) both are reduced after performing only WQ. However, the maximum displacement of 14.6 mm was noticed in the WQ sample which is higher than that of the AR sample. An improvement of 23% in the elongation has proved that the water quenching has increased the ductile behaviour of the Al-alloy but with a loss of UTS and YS. The 3rd sample has shown a good improvement in the UTS value due to ageing followed by water quenching. As compared to the plain WQ sample, the WQ + Ag sample has shown a 6% and 11% increment in UTS and YS, respectively with a negligible loss in ductility. The FC sample (4th) has taken the least amount of force to reach up to its UTS point. Also, the UTS (120.3 MPa) and YS (104.8 MPa) of this sample are the lowest among others. The maximum displacement observed in the

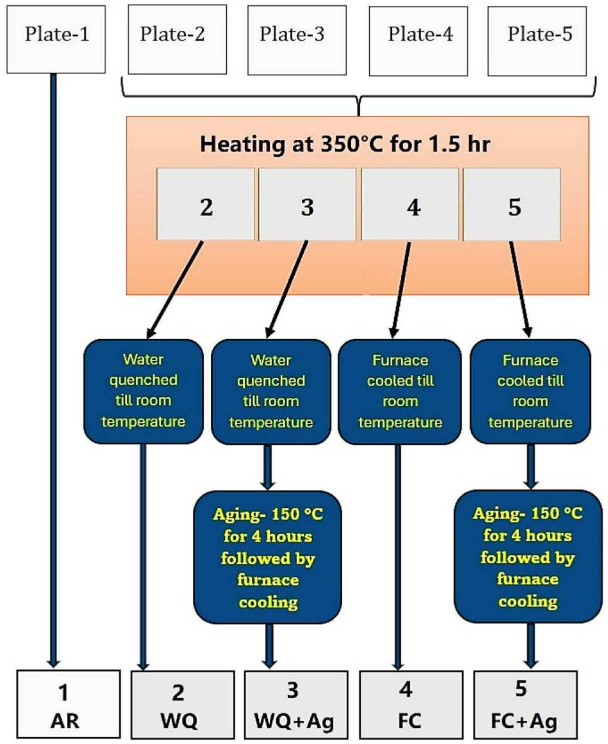

Figure 2. Schematic of the experimental procedure: (AR: As received; WQ: water quenched; Ag: Aged; FC: furnace cooled).

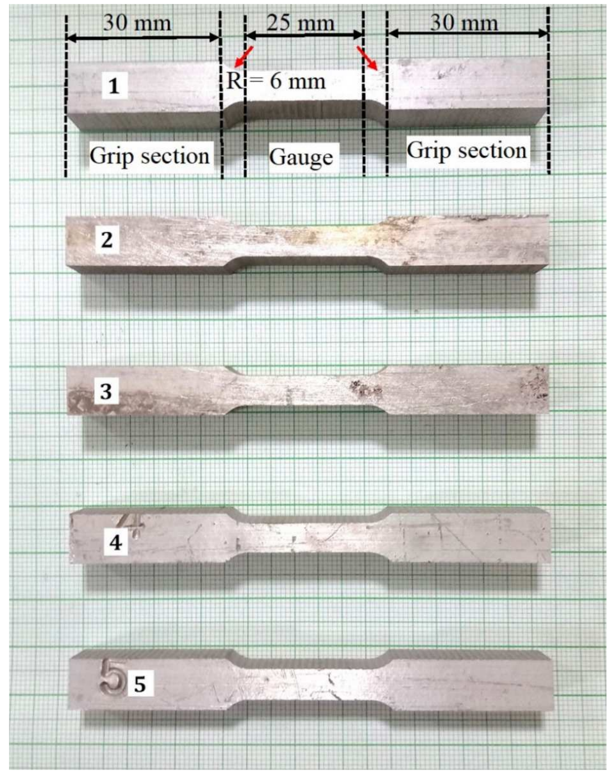

Figure 3. The specimens used for the tensile test are sized according to ASTM-E8 standard.

FC sample is comparable with other heat-treated samples. The FC + Ag sample has shown a slight improvement in the UTS and YS of the sample. As compared to the pure FC sample, the FC + Ag sample has shown 2.5% and 2.8% improvement in the UTS and YS, respectively. Through the tensile test, it can be seen that the most favourable condition for improving the UTS and YS along with ductility is water quenching + ageing. The tensile properties of all the samples are given in Table 2.

There is a small deviation in the initial stage, nearly at 7 MPa of tensile stress, of all the curves in Figure 4. The deviation is starting from a certain point. According to [27], many materials follow Hooke's law to an adequate level in the early (low strain) region of the curve, meaning that stress and strain are proportional. The materials ultimately deviate from this linear proportionality as strain increases; this point of deviation is known as the limit of proportionality. The curve stops being linear at this point. This nonlinearity is typically linked to the specimen's plastic flow caused by stress. Atoms are moved to new equilibrium places because of the rearrangement of the material's intrinsic molecular structure. Hence, for the present work, it may be considered that all the specimens showed a proportional limit at a tensile stress of 7 MPa. However, the proportional limit of 7 MPa is too small for any aluminium alloy. Two other factors may potentially contribute to the early kink formation: first, the specimen may straighten during the early stages of the tensile test, and second, there may be sliding between the specimen and the UTM jaw.

Table 1. Specimen description.

Sr. No	Sample	Physical condition	Sample naming
1	Sample 1	As-received condition	AR
2	Sample 2	Heated at 350°C for 1.5 h of holding time and then quenched in water	WQ
3	Sample 3	Heated at 350°C for 1.5 h of holding time and then quenched in water + ageing	WQ + Ag
4	Sample 4	Heated at 350°C for 1.5 h of holding time and then cooled in a furnace	FC
5	Sample 5	Heated at 350°C for 1.5 h of holding time and then cooled in a furnace + ageing	FC + Ag

Hardness test

The Rockwell hardness test (HRB) was conducted on five different points of each sample and an average value has been calculated. The highest hardness of 91.6 HRB was recorded in the AR sample which is in rolled condition. After WQ, a minor drop has been observed in the hardness due to grain refinement. Further, with the aid of the ageing process to the WQ sample, the hardness value (87.2 HRB) has again decreased in sample 3. This low

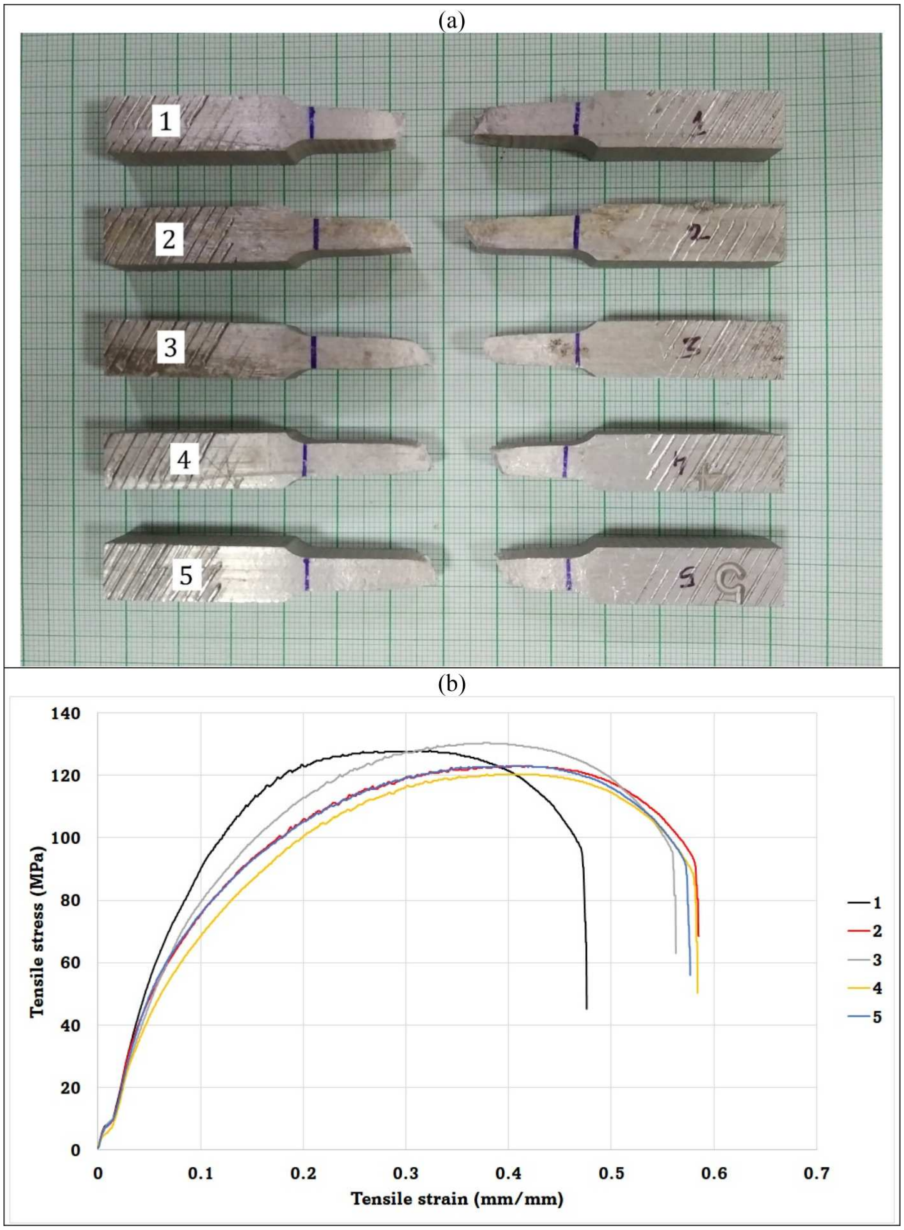

Figure 4. (a) Broken tensile specimens; (b) Stress vs strain graph obtained through the tensile test.

hardness value of the WQ + Ag sample is in good corroboration with its tensile properties as the ductility of this sample was a bit higher than that of the WQ sample. The FC sample has shown the least hardness (81.4 HRB) among all samples. However, the FC + Ag sample has recovered hardness which has been dropped during the furnace cooling process. Overall, the only furnace cooling method is not recommended for theAl 6061 alloy in terms of maintaining the strength and hardness properties. An indicative bar chart has been plotted to clearly observe a comparison among the hardness of different samples (Figure 5).

Table 2. The tensile properties of five samples under study.

Sample	Maximum load (kN)	Ultimate tensile stress (MPa)	Maximum displacement (mm)	Yield load (kN)	Yield stress (MPa)	% Elongation
1	8.0	127.9	11.9	7.3	116.8	31.4
2	7.7	123.0	14.6	6.6	106.0	36.8
3	8.2	130.5	14.1	7.4	117.7	38.0
4	7.5	120.3	14.6	6.5	104.8	37.3
5	7.6	123.0	14.4	6.7	107.8	38.5

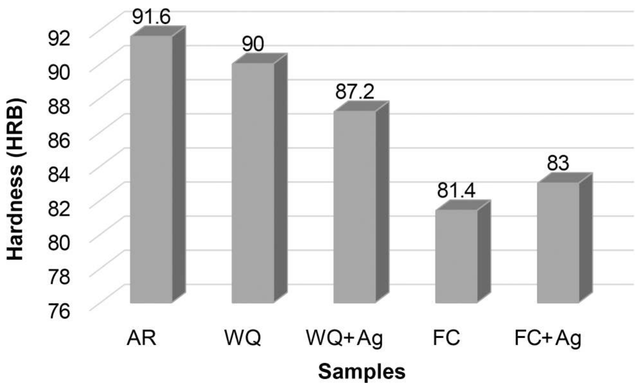

Figure 5. A comparative analysis among hardness of samples.

Optical micrography analysis

The optical microscopic images of the Al 6061 alloy expose three different kinds of observations: primary α-Al as the major bright regions, secondary Mg_2Si precipitates as coarse dark globules, and fine ternary Al-Mg-Si as black dots (Figure 6). α-Al and Mg_2Si can be clearly seen at 200X magnification but for observing the ternary Al-Mg-Si phase, a high magnification of 500X was adjusted in the optical microscope (Figure 7).

During the rolling process, the primary Al grains get elongated in the direction of rolling. At the same time,

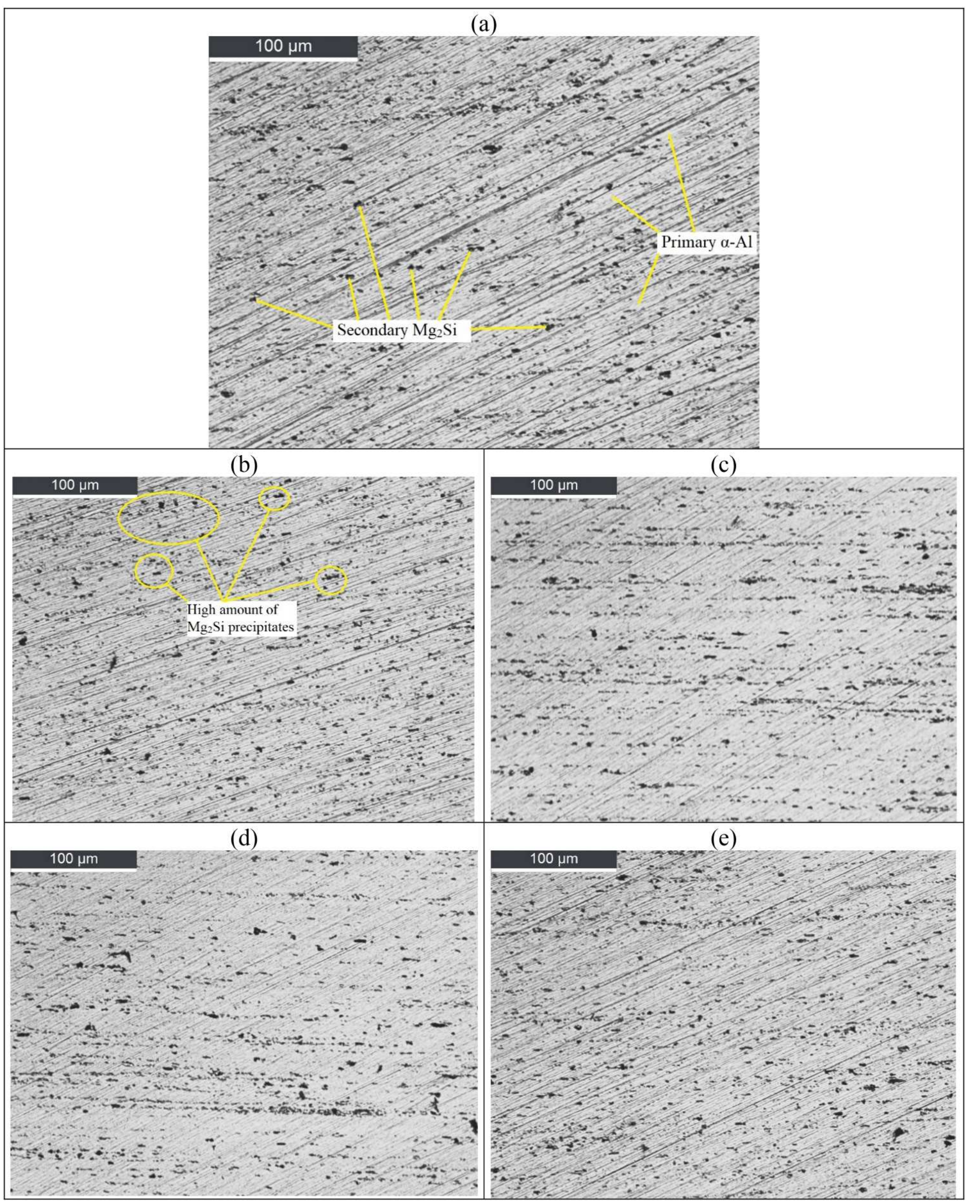

Figure 6. The microstructural images at 200X magnification: (a) AR sample; (b) WQ sample; (c) WQ + Ag sample; (d) FC sample; and (e) FC + Ag sample.

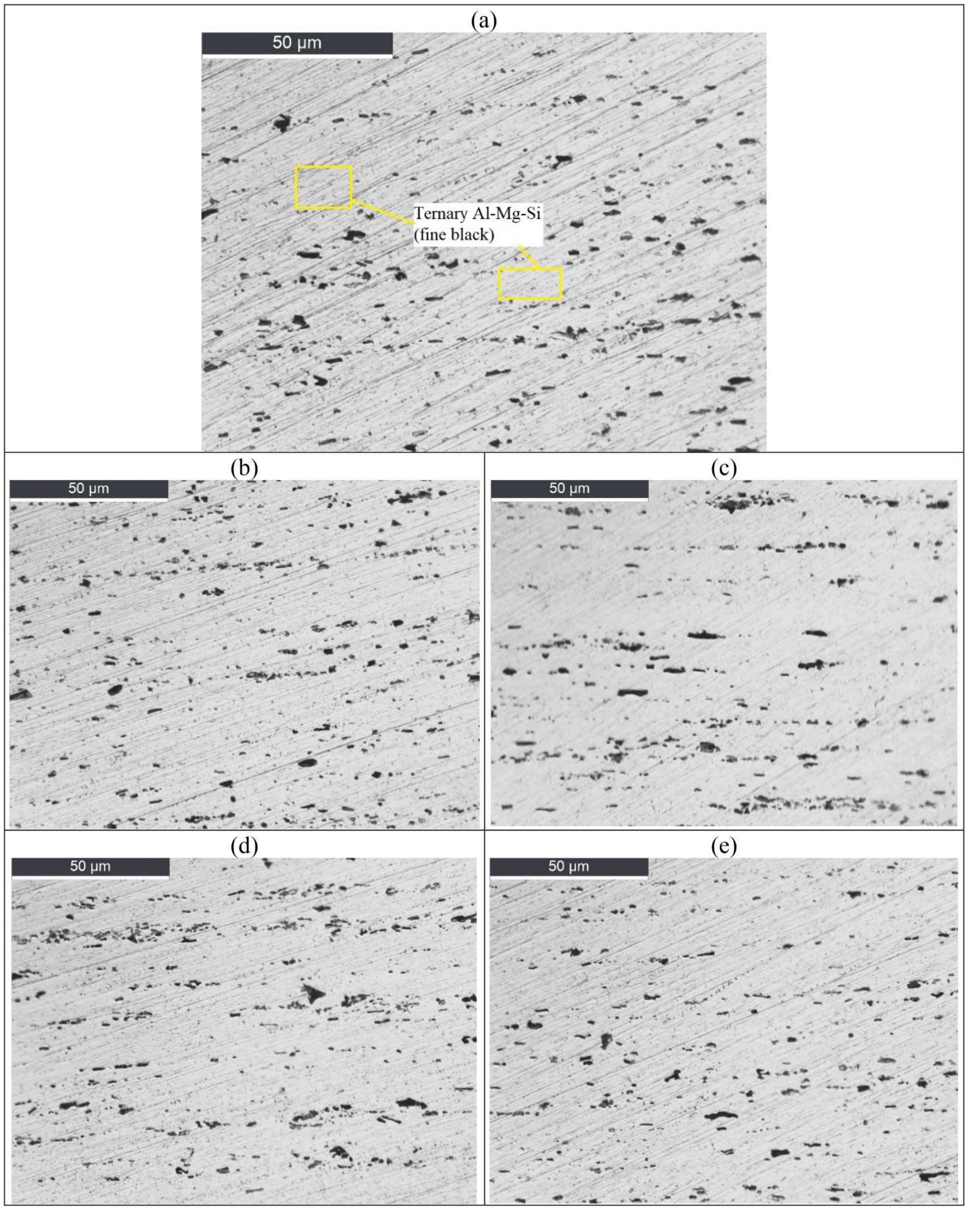

Figure 7. The microstructural images at 500X magnification showing the tiny ternary phase over the primary-Al: (a) AR sample; (b) WQ sample; (c) WQ + Ag sample; (d) FC sample; and (e) FC + Ag sample.

the secondary phase of Mg_2Si makes bands over the bright Al region. As soon as the Al alloys are solution annealed at a temperature range of 350–400°C, elongated α-Al takes an equiaxed shape with an even and thorough distribution of Mg_2Si globules [28–30] (Figure 8).

An increment of Mg_2Si precipitation was noticed in the heat-treated, especially, water-quenched sample. Also, the fine Al–Mg–Si dots are clearly visible in the WQ sample due to the dissolving of alloying elements during solutionising. Compared to the AR sample, there is a significant improvement in the secondary and ternary phases of the heat-treated samples.

XRD analysis

The Al samples have been heated in a closed chamber furnace. As the inner atmosphere was neither a vacuum nor, it was protected by an inert gas, there might be the possibility of oxide formation due to retained oxygen inside the chamber. To check the availability of any foreign compound (like aluminium oxide), an XRD test was conducted on each sample.

Within the 2θ range of 20°–90°, all five samples have shown five intense peaks of Al at different diffraction angles. With reference to [31–33], the Al was seen at various planes such as (111), (002), (022), (113), and

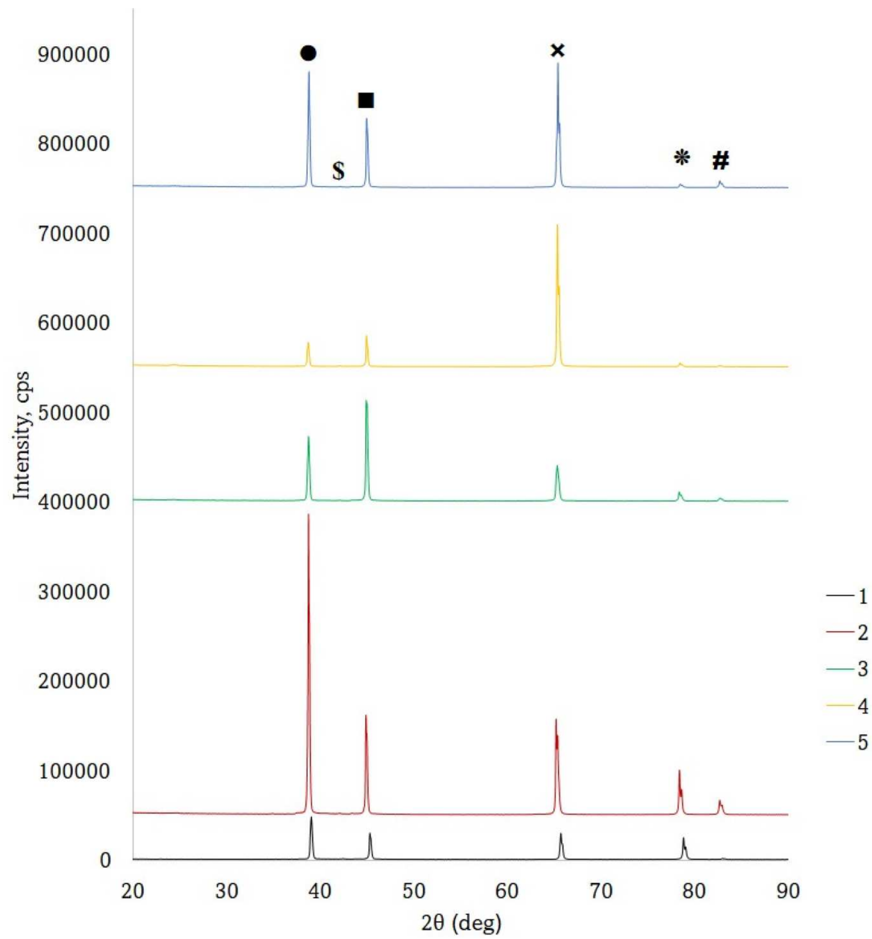

Figure 8. XRD analysis of five samples used under study: [● = Al (111), ■ = Al (002), × = Al (022), ∗ = Al (113), # = Al (222), $ = Mg_2Si].

(222) at 2θ of 39°, 44°, 66.5°, and 78.5°, respectively. The Mg_2Si peak is not significant, yet it was observed at 2θ of 42°. Other than these, no other observation was recorded in the XRD result. Hence, it is clear that no oxide has been formed during heat treatment.

Conclusion

An attempt has been made to conduct and compare different heat treatment methods on Al 6061 alloy plates. The solution annealing + quenching alone and solution annealing + quenching with the aid of ageing have been done during the heat treatment. The tensile, hardness, and microstructural test results indicate the following conclusive remarks:

- The presence of the primary, secondary, and tertiary phases is recognised through microstructural images. Because of the very fine structure, a high magnification was used to observe the Al-Mg-Si phase. All the samples had shown various peaks of Al at similar diffraction angles. There was no contamination on the samples due to heating inside an induction furnace.
- The AR, being available in a hot-rolled state, contains elongated grains and therefore the highest amount of load was applied in this plate to achieve the UTS point. Also, the YS and hardness of this sample are maximum in the AR sample.
- Compared to SA + WQ, the SA + WQ + Ag sample has shown a better combination of UTS, YS, hardness, and ductility although, due to grain refinement, the strength and hardness of heat-treated samples are lesser than those of the AR sample.
- The SA + FC method has shown the maximum drop in the tensile strength and hardness. However, some refinement in the mechanical properties has been observed after following SA + FC + Ag.
- The WQ + Ag is recommended when high strength is required in Al-6061, whereas pure furnace cooling can be adopted to enhance the workability of this alloy.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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