Thermal analysis, microstructure and performance of AA6063 aluminum alloy casting with Ag and Fe additions

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Abstract
This article aims to investigate the microstructure, mechanical properties, wear and corrosion resistance of the grain refined AA6063 Aluminum Alloy Casting with added Ag and Fe. Thermal analysis was used to evaluate the influence of Ag and Fe addition. Reactions are observed during the solidification due to the formation of the $\alpha$-Al dendritic network, followed by the precipitation of the Al8Fe2Si, transformation of Al8Fe2Si into Al5FeSi and/or precipitation of Al5FeSi intermetallic, and finally, the precipitation of small dark particles Mg2Si. Microstructure was examined using optical microscopy, Image analysis and scanning electron microscopy. Hardness, tensile properties, wear and corrosion resistance were evaluated for the as-cast conditions. Line scans for Ag, Fe, Si, Cu and Al were obtained from the various as cast samples using Energy-dispersive x-ray spectroscopy (EDX) facilities.

The results reveal that different intermetallic phases can be formed. These phases are rich in Si, Fe, Mg and Ag. Additionally, AA6063 aluminum alloy casting with added 0.7–0.85 wt% Ag and 0.25–0.95 wt% Fe showed high wear and corrosion resistance response respectively. The wear and corrosion resistance of the AA6063 aluminum alloys with added Ag and Fe resulted were remarkably improved especially at 0.7 wt% Ag addition.

1. Introduction

Due to their light weight, thermal conductivity and excellent strength-to-weight ratio, and the high demand for greater fuel efficiency and higher performance, Al-Si castings are being adapted extensively in application in automobile industry such as pistons, transmission cases, intake manifolds, engine blocks, cylinder blocks and heads [1, 2] Aluminum has replaced steel in automobile wheels, because of its superior heat dissipation during braking, which allows for improved road handling and decreased tie wear. Medium-and high-strength aluminum alloys are widely used in the aerospace industries and marine applications in a variety of forms such as sheet, plate, extrusion, forging, and castings because of their, light weight, excellent extrudability, recycling, excellent corrosion resistance, weldability and immunity to stress corrosion cracking [3–5].

Precipitation hardening AA6063 alloys are widely used in the structural applications, in which the wear resistance is a fundamental design requirement [4, 5]. The AA6063 aluminum alloy contains Mg and Si as the major alloying elements, which are added in balanced proportion and used to precipitate Mg2Si in the heat treated and aged (T6) condition [6]. Magnesium and silicon are present in concentrations around the stoichiometric ratio of the phase Mg2Si. The Si content ranges from 0.35 to 1.3% with Mg ranging from 0.6 to 1.2%. The aim being that finely dispersed particles of this phase precipitate from supersaturated solid solution to give precipitation hardening. This allows good mechanical properties to be obtained by heat treatment. The added alloying elements to AA6063 alloy either dissolve or form intermetallic compounds within the microstructure. Magnesium, copper, zinc and manganese strengthen the aluminum matrix and improve the AA6063 alloy mechanical properties. Zinc-containing phases were not found during solidification process due to the high solubility of Zn in the Al. Titanium, zinc, silver and zirconium also added to improve the alloy
A variety of Fe-containing intermetallic phases (such as Al-Fe, Al-Fe-Si and Al-Fe-Mg-Si phases) are formed in the α-Al dendrite matrix during solidification of AA 6063 alloys depending on alloy composition and solidification condition [8, 9]. In the presence of neutralizing elements such as Mn, Cr, Be, and Ca, the Fe crystallizes in the form of the α-Al15(Fe, Mn)3Si2 script phase at low and intermediate cooling rates (0.1–10 °C/s). The α-Fe-intermetallic is less harmful to the mechanical properties and, hence, preferable to the β-Fe in the casting microstructure due to their compact morphology. Dispersed particles are highly insoluble in aluminum alloys and used to control the grain size at high temperatures. Cooling rate is one of the important variables which influence the microstructure and mechanical properties of alloy castings. A refined structure i.e. dendritic arm spacing (SDAS) and Fe-intermetallic phase are obtained at higher cooling rate (6.25 °C s⁻¹) [10, 11].

Intermetallic particles exist within Al alloys include 1) constituent particles (Al₃Fe, AlFeSi, and Al₅Cu₂Fe); 2) dispersions particles (Al₃Ti, and Al₃Zr); and 3) precipitates (Mg₂Si, MgZn₂, Al₃Cu, and Mg₂Al₃). The effect of different intermetallic particles and alloying additions on the corrosion resistance of 6063 aluminum alloys were assessed by many researchers [12, 13]. However, homogenous dispersion of the precipitates enhance the alloy corrosion resistance. Both constituent and dispersed particles are susceptible to pitting corrosion due to their active and/or noble galvanic interaction with the Al matrix [13]. When the precipitates and/or intermetallic particles are formed on or along the grain boundaries, they may affect the alloy inter-granular corrosion [12]. There is always a tendency for grain boundary zones relatively free from precipitation (PFZ) to be created since the grain boundaries are the most potent vacancy sinks. However, it has been found that trace addition of Ag have a beneficial effect in refining the precipitate structure and removing the (PFZ) which improve the alloy corrosion resistance [14]. The addition of Ag to Al-Cu-Mg systems or Ag and Mg to Al-Cu alloys promotes precipitation of the Ω phase that forms as thin, hexagonal-shaped plates on matrix {111} α planes. It was reported that the Ω phase is responsible for the excellent thermal stability and mechanical properties of the Al-Cu-Mg-Ag alloy casting, which are proposed for high-temperature applications [15, 16].

Thermal analysis technique can be used to monitor the temperature during solidification, and from the temperature—time curves recorded and the first and second derivatives obtained from the cooling rates, numerous useful solidification data can be obtained [11, 17]. Investigation of solidification data, microstructural evolution, hardness, mechanical properties, wear and corrosion behavior of AA6063 aluminum alloy casting with added Ag or Ag plus Zn at low Fe content and added Ag at high Fe content are very necessary to achieve the optimum properties and the better performance in service. Another study will be conducted to investigate the microstructure evolution and alloy performance in the homogenized and T6-temper treated conditions.

2. Materials and methodology

The chemical composition of the base AA6063 Al-Mg-Si alloy used in the present study is listed in table 1. Specimens weighing 300 gm of the base alloy were first cut into smaller pieces, then cleaned, dried and melted in a SiC crucible using an electrical resistance furnace. The molten metal was maintained at a temperature of 850 ± 5 °C. Grain-refiner addition of 2.5 gm of Al-5Ti-1B master alloy was then made to the base alloy melts. The Ag used in the present study for improving corrosion resistance, was added in the form of pure Ag elements, respectively. The Ag levels were 0.70–0.85 wt% Ag and 0.80 wt% Ag plus 0.95 wt% Fe together. The melt was stirred, then degassed for 15 min using pure, dry argon introduced into the melt through a graphite rotary impeller operating at a speed of 150 rpm. Following degassing, the melt was poured at 750 ± 5 °C into graphite molds preheated at 650 ± 10 °C.

Thermal analysis was performed by attaching a high sensitivity thermocouple (chromel-alumel, type K) to the mold system, passing through the bottom of the mold and reaching halfway up into the mold cavity. The temperature-time data was collected using a high-speed data acquisition system linked to a computer with an acquisition rate of 10 readings/sec and connected to the thermocouple. The parts of the thermocouple within

| Table 1. Chemical composition (wt%) of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe. |

| Alloy Code/Alloying | Si    | Cu    | Mg    | Fe    | Zn    | Ag    | Ti    | Cr    | Pb    | Mg/Si | Al    |
|---------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| Base                | 0.564 | 0.003 | 0.774 | 0.301 | 0.014 | 0.004 | 0.058 | 0.150 | 0.003 | 1.372 | Bal.  |
| Base + Ag           | 0.657 | 0.238 | 0.790 | 0.228 | 0.014 | 0.710 | 0.041 | 0.148 | 0.003 | 1.202 | Bal.  |
| Base + Ag + Zn      | 0.687 | 0.262 | 0.976 | 0.262 | 0.847 | 0.847 | 0.056 | 0.148 | 0.003 | 1.420 | Bal.  |
| Base + Ag + Fe      | 0.671 | 0.223 | 0.840 | 0.954 | 0.014 | 0.797 | 0.054 | 0.146 | 0.003 | 1.252 | Bal.  |
the mold were protected using double-walled ceramic tubing. From the thermal analysis data, the cooling curves were plotted and analyzed.

Hardness measurements were carried out on the as-cast samples using a Vicker hardness tester (10 kgf applied load) according to ASTM E92. Each data point on the plots of hardness measurements represents the average of at least five indentation readings. The mechanical properties i.e. ultimate tensile strength, 0.2% offset yield strength and percent elongation were determined in the as-cast AA6063 conditions for the metallic mold without preheating. The tensile tests were conducted on round tension test specimens of diameter 9 mm and gauge length 36 mm using a universal testing machine according to ASTM E8/E8M.

The wear test was performed for AA6063 samples at room temperature using PLINT TE 79 Multi Axis Tribometer Machine (Phoenix Tribology Limited Company). A standard specimen (8 mm diameter and 12 mm length) is prepared; then a computerized pin on disc machine is loaded vertically downwards onto the horizontal disc at a radius of 40 mm (distance between the pin position and center of disk diameter). The test was used for measuring the friction force; friction coefficient and wear rate according to the standards of ASTM G99. The electronic weighing scale was used to find the weight loss of the samples i.e. the mass difference or loss that brought from friction between the AA6063 samples and the disc before and after the test. The disk material made of stainless steel (hardness of 62 HRC) with diameter of 100 mm diameter. The test parameters (velocity (150 rpm) = 0.682 m s⁻¹, time = 600 s, and load = 20 N) were fixed constant for all tested materials. The sliding distance, was calculated by using equation (1) of (L = π'D'RPM''Time, (equation 1)) and the value of 376.8 meters obtained for all sample tested. The base alloy was selected as the reference material for the wear test. Five repetitions were carried out for each experimental treatment and each value represents the average of five readings. Worn surfaces of the as cast AA 6063 specimens were characterized with scanning electron microscope (SEM).

Specimens were corrosion tested using cyclic anodic polarization technique. Samples were polished up to 1200-grit finish, ultrasonically cleaned and rinsed with ethanol and finally dried. A conventional three-electrode cell in a single compartment-cylindrical glass cell was used with a Pt counter electrode. All the potentials were recorded with respect to a saturated calomel electrode (SCE) reference electrode at 25 °C. Sodium chloride medium was prepared from analytical grade chemicals and bidistilled water. The cyclic anodic polarization measurements were performed using a computerized Potentiostat/Galvanostat (Autolab PG STAT 30). Potential was scanned starting from −0.3 V below E_corr in the positive direction (~1 V above E_corr) and then scan direction was reversed until E_corr. Meters; corrosion potential (E_corr), Corrosion current (I_corr) and corrosion rate (CR) were deduced from the polarization curves using the Auto Lab software.

Samples for metallographic examination were sectioned from the prepared castings, mounted, polished and etched (using 1 ml HF (48%) + 200 ml distilled water solution) to examine the precipitate distribution, using both optical and scanning electron microscopy. The microstructure and AlFeSi intermetallic phase particles were analyzed, quantified using Image analysis in conjunction with the optical microscopy and by Image J software. The polished and/or etched surfaces were examined by scanning electron microscopy (SEM) equipped with an energy dispersive x-ray spectrometer (ED) for quantitative chemical analysis of various particles present in the alloy samples. The microstructure was examined for different alloy samples using optical microscope.

3. Results and discussion

3.1. Thermal analysis

In solidification process, with increase the degree of undercooling, liquid becomes thermodynamically unstable and transforms into solid. The rate of this process depends on the solidification cooling rate, and the nucleation as well as growth of crystals formed. The final properties of the cast product are determined by the size and morphology of the formed crystals and the condition under which its nucleation and growth. The solidification data obtained in this work are in agreement with reference to Bäckerud et al [18]. The precipitation temperature was above 600 °C for Al15(Fe, Mn)3Si2 phase and was 580 °C for Mg2Si phase during solidification [10]. For AA6063, solidification starts with the formation of α-aluminum dendrite network at 655–653 °C. Also, Al8Fe2Si precipitates immediately between 618–614 °C, followed by a preitectic reaction at 612 °C, which produces Al5FeSi intermetallic. A quaternary reaction, takes place later at 576 °C and gives Mg2Si phase particle [18]. The precipitation temperature of Al15(Fe,Mn)3Si2 phase during casting process is higher than that of Mg2Si or Si phase. Consequently, Mg2Si and Si could be dissolved into matrix after homogenization treatment, while Al15(Fe,Mn)3Si2 phase is hardly dissolved, which is detrimental to alloy performance [19]. The Zn-containing phases were not found during solidification process due to the high solubility of Zn in the Al.

Thermal analysis was used to understand the solidification process in a quantitative manner, and to be able to make better castings. The results of the base, Ag and/or Fe containing AA6063 Al alloys are summarized in figure 1, where the onset of major parts of the four solidification reactions were observed. A total solidification
cooling rate (SCR) obtained are 0.624 °C s⁻¹, 0.714 °C s⁻¹, 0.647 °C s⁻¹ and 0.65 °C s⁻¹ for the AA6063 base alloy, base alloy plus Ag, base alloy plus Ag and Zn, and the base alloy plus Ag and Fe, respectively. This can be obtained when following the same procedure during melting and solidification processes. Similar cooling rate for all conditions are required to have a comparative study for the effect of additions only, figure 1.

Figure 2 present the solidification data obtained by using thermal analysis technique cooling curve. Figure 2(a) compare the cooling curve and first derivative curve for AA6063 base alloy and the base alloy plus Ag at solidification cooling rates of 0.65 °C s⁻¹. However, figures 2(b)–(c) show the cooling rates, first derivatives and second derivatives for AA6063 base alloy plus Ag, base alloy plus Ag and Zn, and base alloy plus Ag and Fe at solidification cooling rates of 0.714 °C s⁻¹, 0.647 °C s⁻¹ and 0.65 °C s⁻¹ respectively.

Peak numbers #1, #2, #3, and #4 that were presented in figures 2 and 3 stand for the main reactions obtained during solidification. The main reactions are observed during solidification correspond to the formation of the α-Al dendritic network (peak #1), followed by the precipitation of the light gray Al8Fe2Si intermetallic particles (peak #2), and the transformation of Al8Fe2Si into the brown Al5FeSi needles phase and the precipitation of small dark particles Mg2Si (peaks #3 and #4). Solidification data i.e. the reaction solidification temperature and time (TM and T) corresponding the four reactions i.e. peak numbers #1, #2, #3, and #4 expected to occur during solidification of the base alloy AA6063 with different conditions were presented in figure 3.

The nucleation temperature (TN) is defined as the temperature corresponding to the first noticeable change on the derivative of the cooling curve, where nucleation behavior noticeably changed heat flow; the minimum temperature (TM) was the minimum temperature prior to recalescence; and the growth temperature (TG) was the maximum reaction temperature reached after recalescence, and the (TS) is the end of solidification temperature. Solidification data for the base alloy AA6063 with different conditions were listed in table 2. Al nucleation temperature (TN), minimum reaction temperature (TM), reaction growth temperature (TG) and the end of solidification temperature (TS) for Al-dendritic phase obtained at an average solidification cooling rate of 0.15 °C s⁻¹ are listed in table 2. Similar to Al-dendritic phase, solidification data for Al8Fe2Si intermetallic particles, Al5FeSi needles phase and Mg2Si phase obtained at average solidification cooling rates of 0.52 °C s⁻¹, 1.25 °C s⁻¹ and 1.3 °C s⁻¹, respectively are listed in table 2. Only the AA6063 base alloy with added Ag plus Zn exhibits a high solidification cooling rate for Al-dendritic phase (0.61 °C s⁻¹) and a low one for Al5FeSi phase (0.56 °C s⁻¹).

It was observed that nucleation temperature (TN) and time (tN), solidification reaction temperature (TM) and time (tM) and end of solidification temperature (TS) and time (tS) of the Al-dendritic phase were reduced for the AA6063 base alloy with added Ag (i.e. 0.85 wt%Ag) plus Zn (i.e. 0.85 wt%Zn) at low Fe content (i.e. ∼0.25 wt%Fe). Moreover, the added Ag plus Zn have significant effect on the solidification data of the Al8Fe2Si phase. In case of Al5FeSi and Mg2Si phases, the AA6063 base alloy with added Ag plus Zn have significant effect on.
on decreasing the solidification time only. Similar behavior was observed when Ag added (i.e. 0.70 wt%Ag) only at both low and high Fe content but with lesser effect than the added Ag plus Zn. The effect of added Ag (i.e. 0.80 wt%Ag) at high Fe content (i.e. 0.95 wt%Fe) on the nucleation temperature (TN), solidification reaction temperature (TM) and of solidification temperature (TS) were observed for Al-dendritic, Al8Fe2Si, Al5FeSi and Mg2Si phases. Only high solidification reaction temperature (TM) was obtained for Mg2Si phase.

Considering the change in the nucleation temperature of Al dendrite phase, addition of Ag at low and high Fe content to the AA6063 base alloy caused a depression in the Al nucleation temperature by about 1.56 °C and 2.03 °C, respectively. With reference to the solidification reaction temperature (TM) of Al dendrite phase for the base alloy (i.e. 652.6 °C), the depression in solidification reaction temperature is about 1.88 °C and 1.97 °C due to the added Ag and the added Ag plus Zn at low content of Fe to the AA6063 base alloy, respectively. However, there is an increase of solidification reaction temperature by 0.13 °C with the added Ag at high content of Fe.

The addition of Ag plus Zn to the AA6063 base alloy decrease the precipitation or nucleation temperature of Al8Fe2Si phase by 6.48 °C (i.e. from 649.23 °C to 642.75 °C). However, the additions of of Ag to the AA6063 base alloy at low and high Fe content decrease the solidification reaction temperature of Al8Fe2Si phase by 2.76 °C and 3.77 °C, respectively. In case of added Ag and Zn to the base AA6063 alloy, an increase of 3.8 °C in the Al8Fe2Si phase solidification reaction temperature was obtained. The nucleation temperatures of 649.23 °C, 649.98 °C and 648.9 °C were obtained for Al8Fe2Si phase when the Ag was added to the base alloy with low Fe content and with high Zn and Fe content, respectively. Again, the nucleation temperature for Al5FeSi phase was dropped from 608.77 °C to 601.49 °C when the Ag was added to the base alloy with high Fe content. The solidification reaction temperature was decreased sharply to 603.7 and 595.68 °C (i.e. reduced by 5.07 °C and 13.09 °C) when the Ag was added to the base alloy with low Fe content and with high Zn and Fe content, respectively, table 2. The nucleation or precipitation temperature of Mg2Si phase was decreased from 589.46 °C to 583.47 °C, 585.2 °C and 581.3 °C when the Ag was added to the base alloy with low Fe content and with high Zn and Fe content, respectively. Also, the solidification reaction temperature was increased from 559.73 °C to 569.59 °C, 563.3 °C and 567.57 °C for the same additions, respectively, table 2.

Figure 2. Solidification curves and their first and second derivatives obtained and the main reactions observed during solidification (a) for the AA6063 base alloy with low Fe content, (b) the base alloy with added Ag at low Fe content, (c) the base alloy with added Ag at low Fe and high Zn-content and (d) the base alloy with added Ag at high Fe-content. Peak #1, α-Al dendrite, peak #2, Al8Fe2Si intermetallic and, peaks #3 and #4 Al5FeSi intermetallic and Mg2Si phases, respectively.
3.2. Microstructure of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe

The as-cast microstructure of Al−Mg−Si alloy may include β-AlFeSi, α-AlFeSi, π(Al8Si6Mg3Fe), AlCuMgSi, Mg2Si, Si, and θ(Al2Cu) [19]. Constituent particles are large in size and are formed during solidification, and are rarely dissolved during subsequent homogenization treatment or thermomechanical processing. The circular shaped or eutectic AlCuMgSi phase of hexagonal crystal structure is easily dissolved into matrix during subsequent homogenization process. There are two kinds of Mg2Si phases in the as-cast structure. One phase is face-center cubic and is formed during solidification process. This phase is distributed along grain boundary with large size and rod-like morphology. The other Mg2Si phase is hexagonal and needle-shaped morphology, which is formed with small size at the very fast cooling rate after the casting process is finished [20].

Figure 4 shows examples of optical microstructures obtained from AA6063 base alloy and base alloy plus high Ag and low Fe, base alloy plus high Ag and Zn and low Fe, and base alloy plus high Ag at solidification cooling rates of 0.65, 0.714 °Cs−1, 0.647 °Cs−1 and 0.65 °Cs−1 respectively. The presence of α-Fe compact script intermetallic phase in the base AA6063 alloy sample is observed (figure 4(a)), while the presence of β-Fe platelets intermetallic phases in the high Ag-containing AA6063 alloy samples at low and high Fe content are observed (figures 4(b) and (d)). Other interesting aspects of the AlFeSiNiCu-rich and AlFeSiAgCu-rich – intermetallic phase observed in the high Ag-containing AA6063 alloy samples by the optical micrographs of figures 4(b) and (c) which reveal a discontinuous precipitate along the grain boundaries. The presence of AlFeSiNiCu-rich and discontinuous AlFeSiNiCu-rich intermetallic particles within the grain boundary and within the α-Al dendrite are also observed in figure 4(b).

Figure 5 displays the microstructure (Optical and SEM micrographs) of the base AA6063 alloy at solidification cooling rates (SCR) of approximately 0.62 °Cs−1. Examples of Optical and SEM micrographs in the as-cast condition, figures 5(a), (b). The presence of both α-Fe compact script intermetallic and β-Fe platelets intermetallic phases in the base AA6063 alloy sample containing 0.3 wt%Fe are observed (figure 5(a)).

Figure 3. Solidification reaction temperature (Tm) and time (tm) for Al, dendritic, AlFe2Si, Al5FeSi and Mg2 Si. Phases observed in the AA6063 base alloy with low Fe content, the base alloy with added Ag at low Fe content, the base alloy with added Ag at low Fe and high Zn-content and the base alloy with added Ag at high Fe-content. (a) Solidification Reaction Temperature and (b) Solidification Reaction Time.
Table 2. Solidification Data obtained for AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe.

(Peak #1): Liq $\rightarrow$ Al, dendrite

| Alloy Code | $T_{N}^{Al}$ | $t_{N}^{Al}$ | $T_{M}^{Al}$ | $t_{M}^{Al}$ | $T_{C}^{Al}$ | $t_{C}^{Al}$ | $T_{S}^{Al}$ | $t_{S}^{Al}$ | $\Delta T_{N}^{Al}$ | $\Delta t_{N}^{Al}$ | SCR = $\Delta T/\Delta t$ |
|------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|-----------------|-----------------|------------------|
| Base       | 655.35       | 17.8         | 652.6        | 27           | 652.47       | 33.3         | 649.23       | 61.2         | 8.55            | 49.3            | 0.14             |
| Base + Ag  | 653.79       | 16.6         | 650.72       | 20.8         | 650.4        | 27.8         | 649.98       | 46.4         | 3.81            | 29.8            | 0.13             |
| Base + Ag + Zn | 654.2   | 4.4          | 650.63       | 6.5          | 648.12       | 11.5         | 642.75       | 23.1         | 11.45           | 18.7            | 0.61             |
| Base + Ag + Fe | 653.32 | 18           | 652.73       | 22.2         | 650.5        | 39           | 648.9        | 43.5         | 3.32            | 22.5            | 0.17             |

(Peak #2): Liq $\rightarrow$ Al$_{8}$Fe$_{2}$Si

| Alloy Code | $T_{N}^{Al8Fe2Si}$ | $t_{N}^{Al8Fe2Si}$ | $T_{M}^{Al8Fe2Si}$ | $t_{M}^{Al8Fe2Si}$ | $T_{C}^{Al8Fe2Si}$ | $t_{C}^{Al8Fe2Si}$ | $T_{S}^{Al8Fe2Si}$ | $t_{S}^{Al8Fe2Si}$ | $\Delta T_{N}^{Al8Fe2Si}$ | $\Delta t_{N}^{Al8Fe2Si}$ | SCR = $\Delta T/\Delta t$ |
|------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|-------------------|---------------------------|---------------------------|------------------|
| Base       | 649.23            | 61.2              | 630.7             | 102.6             | 608.77            | 137.6             | 40.46            | 76.4              | 0.53                      |                           |                  |
| Base + Ag  | 649.98            | 46.4              | 634.5             | 91.5              | 615.4            | 112.2             | 34.55            | 65.8              | 0.52                      |                           |                  |
| Base + Ag + Zn | 642.75 | 23.1          | 627.94            | 51.2              | 616.89           | 74.9              | 25.86            | 51.8              | 0.5                      |                           |                  |
| Base + Ag + Fe | 648.9  | 43.5          | 626.93            | 95.5              | 601.49           | 131.3             | 47.41            | 87.8              | 0.54                      |                           |                  |

(Peak #3): Liq + Al$_{8}$Fe$_{2}$Si $\rightarrow$ Al + Al$_{5}$FeSi

| Alloy Code | $T_{N}^{Mg2Si}$ | $t_{N}^{Mg2Si}$ | $T_{M}^{Mg2Si}$ | $t_{M}^{Mg2Si}$ | $T_{C}^{Mg2Si}$ | $t_{C}^{Mg2Si}$ | $T_{S}^{Mg2Si}$ | $t_{S}^{Mg2Si}$ | $\Delta T_{N}^{Mg2Si}$ | $\Delta t_{N}^{Mg2Si}$ | SCR = $\Delta T/\Delta t$ |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------------------------|-------------------------|------------------|
| Base       | 589.46          | 137.6           | 559.73          | 175.6           | 554.1           | 180             | 35.36           | 26.3             | 1.34                    |                          |                  |
| Base + Ag  | 583.47          | 135.7           | 563.28          | 149.8           | 554.4           | 157.1           | 30.05           | 21.4             | 1.4                     |                          |                  |
| Base + Ag + Zn | 585.2   | 131.7          | 569.59          | 145.7           | 555             | 157.6           | 30.2            | 25.9             | 1.16                    |                          |                  |
| Base + Ag + Fe | 581.32 | 148.5          | 567.57          | 159             | 550.8           | 172             | 30.52           | 23.5             | 1.3                     |                          |                  |
spectra of point’s c and d in figure 5(b) are displayed in figures 5(c) and (d), respectively. The precipitation of a sludge particle ([Al\(_{3.2}\)Fe\(_{2.09}\)Si\(_{1.12}\)Mg\(_{0.11}\)Mn\(_{0.078}\)Ag\(_{0.056}\)]) point a, Al\(_{5.8}\)SiMg\(_{0.12}\)Ni\(_{0.1}\)Ag\(_{0.03}\) not presented, Al\(_{10.9}\)Si\(_{0.34}\)FeMg\(_{0.1}\)Ag\(_{0.07}\) point b in figure 5(a)) Al\(_{9.6}\)Si\(_{0.31}\)Fe\(_{0.97}\)Mn\(_{0.03}\)Ag\(_{0.06}\) point b) in figure 5(c). Also, the EDS analysis of particle (point c) shown in figure 5(c) was Al\(_{8}\)SiFe\(_{1.05}\)Mg\(_{0.4}\)Ag\(_{0.03}\)Ni\(_{0.03}\). However, The EDS analysis of the matrix was Al\(_{52.76}\)Ag\(_{0.54}\)Mg\(_{0.45}\) or Al\(_{39.65}\)Si\(_{0.18}\)Ag\(_{0.37}\)Mg\(_{0.44}\) which indicate that Both Ag, Si and Mg form solid solution with the Al dendrite matrix.

Figure 6 display the microstructure and line scans for the AA6063 alloy (0.7 wt% Ag) at low Fe content (∼0.25 wt% Fe) after solidification at the rate of approximately 0.71 °Cs\(^{-1}\). The EDS spectra of point (a) in figure 6(c), which is presented in figure 6(d) show the formation of Al\(_{14.6}\)Si\(_{1.3}\)Ag\(_{0.13}\), while point (b) in the same figure 6(c) show the formation of Al\(_{10.4}\)Fe\(_{0.85}\)Si\(_{0.5}\)Ag\(_{0.12}\) intermetallic phases. Other intermetallic of Al\(_{9}\)Si\(_{0.82}\)Fe\(_{0.82}\)Ag\(_{0.06}\) intermetallic (not presented) and Al\(_{14}\)Si\(_{0.56}\)FeCu\(_{3}\)Mg\(_{0.68}\) point c in figure 6(b) (not presented), Al\(_{23.2}\)Fe\(_{0.33}\)Ag\(_{0.2}\), Al\(_{14.6}\)Si\(_{0.34}\)Fe\(_{0.06}\)Ag\(_{0.13}\) and Al\(_{27}\)Si\(_{0.3}\)Fe\(_{0.06}\)Ag\(_{0.34}\) (not presented) are observed in the microstructure. Also, the EDS analysis of Si particle (not presented) was Al\(_{0.77}\)Si\(_{0.01}\). However, The EDS analysis of the matrix was Al\(_{5}\)Mg\(_{0.01}\)Ag\(_{0.01}\) which indicate that Both Mg and Ag form solid solution with the Al dendrite matrix.

Optical, SEM micrographs and line scans taken from the as-cast condition, display the microstructure of the high Ag plus Zn- containing AA6063 alloy after solidification at the rate of approximately 0.65 °Cs\(^{-1}\), figure 7. Al-dendrites and grain boundaries intermetallic precipitation are observed in figures 7(a)–(c). The EDS spectra taken for point (a) in figure 7(b) show the Al\(_{8.3}\)Fe\(_{0.85}\)Si\(_{0.5}\)Ag\(_{0.08}\)Cu\(_{0.05}\)Zn\(_{0.02}\). Also, the formation of Al\(_{15}\)Si\(_{0.37}\)Ag\(_{0.13}\)Cu\(_{0.1}\) (Fe\(_{0.94}\)Mn\(_{0.06}\)), Al\(_{14}\)SiFe\(_{0.06}\)Cu\(_{0.65}\)Ag\(_{0.15}\) and Al\(_{15}\)SiFe\(_{0.76}\)Mg\(_{0.17}\)Ag\(_{0.13}\) intermetallic (not presented) are observed in the microstructure. Again the EDS analysis of Si particles observed within the aluminum matrix are Al\(_{5}\)Si\(_{0.37}\)Ag\(_{0.13}\)Cu\(_{0.1}\) and Al\(_{3}\)Si\(_{0.38}\)Mg\(_{0.09}\)Fe\(_{0.04}\)Ag\(_{0.09}\)Ag\(_{0.02}\). However, The EDS analysis of the aluminum matrix taken at different points is Al\(_{26.6}\)Si\(_{0.3}\)Cu\(_{0.2}\)Ag\(_{0.34}\) (not presented) or Al\(_{52.7}\)Mg\(_{0.38}\)Ag\(_{0.62}\) which indicate that Both Si, Cu, Mg and Ag form solid solution with the Al dendrite.
matrix. Copper present in the high Ag-containing AA6063 alloys either goes in solid solution with the aluminum matrix (Al26.62Si0.2Cu0.12Mg0.34Ag0.34) or form Al6.2SiMg1.14Cu0.23Fe0.05Ag0.06 intermetallic phase.

Figure 8 displays the microstructure and line scans for AA6063 alloy with 0.8 wt% Ag and 0.95 wt% Fe addition after solidification at the rate of approximately 0.66 °C s⁻¹. Optical and SEM micrographs taken from the as-cast condition show the Al-dendrites and Fe-network intermetallic precipitation, figures 8(a)–(c). The EDS spectra taken in figure 8(d) show the formation of Al15.7SiFe0.85Mg0.32Ag0.1, Al9.9SiFe1.3Ag0.1 and Al7.97SiFe1.16Ag0.029 intermetallic (not presented). Also, the EDS analysis of a white particle (observed in a micrograph not presented) was Al3.3SiCu0.47Mg0.23Ag0.13. However, The EDS analysis of the matrix was Al52.76Ag0.54Mg0.45 or Al39.65Si0.18Ag0.37Mg0.44 (not presented).

To better understand these observations, x-ray mapping of intermetallic phases found in the base alloy, the base alloy with added 0.7 wt% Ag, 0.8 wt% Ag, and 0.8 wt% Ag plus 0.95 wt% Fe were presented in figures 9–12, respectively. It is evident that the addition of Ag and Fe resulted in the formation of intermetallic phases. Backscattered image (CP) taken from the base AA 6063 aluminum alloy and the corresponding x-ray images of Ag, Fe, Si, Al, and Cu are presented in figure 9. However, the backscattered image (CP) of the AA 6063 alloy with added 0.7 wt% Ag and the corresponding x-ray images of Ag, Fe, Si, Al and Cu are shown in figure 10.

Grain size measurement (the ASTM grain size number and the mean intercept length (μm)) of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe were obtained in table 3. Fine grain size are obtained for AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe. Fe-intermetallic and Mg2Si particle characteristics of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe are obtained in tables 4 and 5, respectively. The Ag and Zn additions have some refining and modification effect on the AlFeSi-intermetallic and Mg2Si phase particles formed during the solidification of the AA6063 aluminum casting at low Fe levels. A decrease of their size, volume fractions and aspect ratio obtained. Moreover, an increase in their shape descriptors (i.e. circularity, roundness and solidity) are obtained in comparison to the Ag addition at low or high Fe content, tables 4 and 5. In this work, different Fe-intermetallic phases such as Al9.58Si0.31Fe0.97Mn0.03Ag0.06 or...
Al14Si0.56FeCu3Ni0.68, Al15.55Si0.37Ag0.13Cu0.1 (Fe0.94Mn0.06), and Al7.97SiFe1.16Ag0.029 phases are detected in the microstructure of AA6063 alloy when 0.7 wt% Ag, 0.85 wt% Ag plus 0.85 wt% Zn and 0.8 wt% Ag plus 0.95 wt% Fe are added, respectively.

3.3. Mechanical properties of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe

Addition of Mg to Al-Si alloys leads to the precipitation of \( \pi \)-Fe \((Al_{8}Mg_{3}Fe_{6})\), \(Al_{5}MgCu_{2}Si_{6}\) and \(Mg_{2}Si\) intermetallic. Solution heat treatment affects the dissolution and fragmentation of the \( \beta \)-Fe-intermetallics in the aluminum matrix. A reduction in \( \pi \)-Fe phase surface fraction and change of the \( \beta \)-Fe phase needles morphology occur due to the dissolution, thinning, necking, and fragmentation after solution heat-treatment. Iron-intermetallic morphology, size, and distribution are the main parameters expected to control the mechanical properties. Any amount of Fe up to about 0.8% Fe, increases strength and hardness but slightly reduces ductility. Above 0.8%Fe, both strength and elongation deteriorate rapidly.

The mechanical properties of the base, Ag and/or Fe AA6063 alloys are presented in figure 11. The Ag and Zn added AA6063 alloys exhibit high hardness, ultimate tensile strength and percent elongation levels compared to the base alloys. This may be explained on the basis of cooperative precipitation of \(MgZn_{2}\) and \(Mg_{2}Si\) phase particles, compared to only \(Mg_{2}Si\) precipitation in the other alloys. Only in the case of the Ag-added alloys, they display yield strength values that are equal to or slightly higher than other alloys. In the case of Ag plus Fe-containing alloys, they show lower percent elongation values than other alloys, figure 11. This may be explained on the basis of higher levels of Zn and Mg in the Ag plus Zn containing AA6063 Al-Mg-Si alloys, where the Zn and Mg content were 0.85, 0.976, respectively. The hardness for the base alloy show low levels as a result of the low Mg content of this alloy (0.77 wt%Mg) versus 0.98 wt% Mg for the base alloy plus Ag and Zn and 0.84 wt% Mg for the base alloy plus Ag and Fe alloys.

The mechanical properties (tensile strength, yield strength and percent elongation) of AA6063 aluminum base alloy and the different samples are illustrated in figure 11. The tensile strength of the base alloy (115.4 MPa) is remarkably improved with adding Ag and Ag plus Zn (123.8 MPa and 153.1 MPa, respectively). The tensile
strength value of the added Ag plus Fe sample is almost 1.27 (147.2 MPa) of the base alloy. The yield strength of the base alloy (76.3 MPa) is remarkably improved with adding Ag and Ag plus Zn (97.5 MPa and 96.8 MPa, respectively). The yield strength value of the added Ag plus Fe sample is almost 1.22 (93.2 MPa) of the base alloy. The percent elongation of the base alloy (16.1%) is remarkably improved with adding Ag plus Zn (18.7%). The percent elongation strength value is increased up to 16%. The percent elongation value of the added Ag and Ag plus Fe sample is almost 0.85 (13.6%) and 0.67 (10.7%) of the base alloy respectively. The hardness of AA6063 aluminum base alloy and the different samples are illustrated in figure 12. The hardness of the base alloy (38HV) is remarkably improved with adding Ag and Ag plus Zn (45 and 63HV, respectively). The hardness value is increased up to 18% and 65%, respectively. The hardness value of the added Ag plus Fe sample is almost 1.45 (55HV) of the base alloy. The significant hardness increment is mainly due to the combined effect of the presence of hard matrix and intermetallic particles throughout the matrix.

Fracture surface taken from the as-cast AA6063 base alloy, base alloy plus high Ag and low Fe, base alloy plus high Ag and Zn and low Fe, and base alloy plus high Ag and Fe at solidification cooling rates of 0.65, 0.714 °C s\(^{-1}\), 0.647 °C s\(^{-1}\) and 0.65 °C s\(^{-1}\) respectively are displayed in figure 13. The presence of \(\alpha\)-Al dendrite phase are observed in all micrographs in figures 13(a)–(d). Discontinuous precipitate particles (large and small) inside dimples are observed in figure 13(c). Large dimples around hard intermetallic \(\beta\)-Al5FeSi and \(\alpha\)-Al8Fe2Si particles, while smaller around dispersive hardening \(\beta\)-Mg2Si, and Si or even AlCuMgSi precipitate phase, figures 13(b) and (c). Both of micro cracks and grain boundary voids are observed in figure 13(d). Dimples and dendritic structure and ductile fracture are dominant in (a), (b) and (c), however hear oval dimple formed after micro cracks and voids coalescence, figure 13(d).

### 3.4. Wear resistance

The observed increase in hardness and wear resistance may be explained due to the fine grain size and the refined AlFeSiAg-rich intermetallic particles and Mg2Si phase obtained after adding Ag plus Zn or Ag to the AA6063.

![Figure 7.](image-url)
base alloy, table 6 the result of this work are in agreement with reference [21], where the increase in hardness and wear resistance for AA6063 alloys are related to the formation of Mg2Si, AlFeSi and CuAl2 phases [21]. Addition of Ag to AA6063 Alloy casting at low and high level of Fe-content or at high Zn content improve wear resistance due to the refining and modification of AlFeSi-intermetallic and Mg2Si phase particles formed during the solidification. Fine magnesium silicide and Al15.55Si0.37Ag0.13Cu0.1(Fe0.94Mn0.06) intermetallic particles within the grain boundaries of the Al dendrite matrix. The presence of Manganese, silver and cobber enhances the formation of the α-Fe-intermetallic Al15.55Si0.37Ag0.13Cu0.1(Fe0.94Mn0.06) rather than the β-Fe-intermetallic phase. Coefficient of friction is determined by the ratio of the frictional force to the loading force on the pin. Friction coefficient was reported in table 6. The mass loss results can be used to compare materials of equivalent densities. Equation (2) (i.e. Volume loss (mm³) = Mass loss (Kg)/Density (g/cm³), (equation 2)) used for conversion of mass loss to volume loss, where, the density of AA6063 is taken as 2.69 g cm⁻³ [3–5]. The steady state wear rate was calculated [22] using equation (3) (i.e. Wear rate (mm³ m⁻¹) = Mass loss (g)/Density (g/mm³) * Sliding Distance (m), (equation 3)). Measured data, Friction coefficient, and calculated wear rate i.e. weight loss (kg)/sliding distance (m) or wear rate i.e. volume (mm³)/sliding distance (m) are listed in table 6.

Figure 14 shows the variations of weight losses of the AA6063 with added Ag and Fe together with the base alloy, after subjected to pin-on-disk dry sliding wear test at a fixed load of 20 N in air at room temperature. Compared with the base alloy, all the AA6063 with added Ag and Fe samples have excellent wear properties under dry-sliding wear test condition. The weight loss of 0.7 wt% added Ag sample is almost 43.5% of the AA6063 base alloy sample. This remarkable wear resistance improvement came from the hard, stable, wear resistant fine Mg2Si and Fe intermetallic particles (Al15.55Si0.37Ag0.13Cu0.1(Fe0.94Mn0.06) and Al7.97SiFe1.16Ag0.029), which homogenously precipitated inside the Al-matrix. However, The EDS analysis of the matrix was Al51.35Si0.14Mg0.37Ag0.48 which indicate that Both Si, Mg and Ag form solid solution with the Al dendrite matrix. The Cu present in the AA6063 alloy with addition of Ag and Fe form Al7SiMgCu0.69Ni0.63Fe0.09Ag0.04 intermetallic. Moreover, the grain refinement of the matrix also helps in improvement the wear characteristics.

The wear resistance of the AA6063 base alloy is remarkably improved with adding Ag, Ag plus Zn, and Ag plus Fe. The wear loss value is decreased up to 43.5%, 45% and 44.5% respectively when using graphite mold
casting with preheat at 650 °C. By adding Ag plus Zn, the weight loss is decreased to 45% of the base alloy sample. This is may be explained due to the more precipitated fine magnesium silicide and Al15.55Si0.37Ag0.13Cu0.1 (Fe0.94Mn0.06) intermetallic particles within the grain boundaries of the Al dendrite matrix. The wear resistance of the AA6063 base alloy is remarkably improved with adding Ag, Ag plus Zn, and Ag plus Zn. The wear loss value is decreased up to 43.5%, 45% and 44.5% respectively with using graphite mold casting with preheat at 650 °C. Figure 13 present the wear rate for the 6063 aluminum base alloy with Ag, Ag plus Zn, and Ag plus Fe additions using preheated graphite mold at 650 °C. It can be seen that Ag plus Zn, Ag and Ag plus Fe addition to the base alloy decrease the wear rate. A severe adhesive wear was observed on the base sample without Ag or Fe addition as shown in SEM images in figure 15. Consequently, the width of the wear track enlarged as the contact area between the pin and the as-cast sample increased. The width of the wear track decreased with the added Ag and Ag plus Zn or Fe samples, figure 15. The amount of the debris removed from the base sample toward the sides of the wear track was much more than that in the added Ag and Ag plus Zn and Ag plus Fe samples.

3.5. Corrosion resistance
Comparing the AA6063 base alloy sample to the base alloy with added Ag, Ag plus Zn and Ag plus Fe reveals that the corrosion potentials ($E_{\text{corr}}$) of base alloy sample with added Ag plus Zn and Ag plus Fe shift considerably in the noble (positive) direction showing values as low as $-0.730$ while base alloy shifts markedly in the active (negative) direction showing $E_{\text{corr}}$ of $-1.12$. According to the corrosion rates of the AA6063 base alloy with added Ag gives a very low corrosion rate ($0.007 \text{ mm year}^{-1}$) in comparison to other samples, table 7. The corrosion resistance of the AA6063 base alloy is remarkably improved with adding Ag, Ag plus Zn, and Ag plus Zn. The corrosion rate value is decreased up to 81%, 68% and 65% respectively when using preheated graphite mold casting at 650 °C, figure 16. The observed increase in corrosion resistance may be explained due to the fine size of the Fe- and Ag-intermetallic particles and the elongated intermetallic particles appeared on the Al grain boundaries and distributed in the Al-matrix. The fine grain size and the refined AlFeSi intermetallic and Mg2Si obtained after adding Ag or Ag plus Zn to the AA6063 base alloy improve the alloy wear and corrosion resistance. The AlFeSiAg-rich intermetallic particles formed within the $\alpha$-Al dendrite and were homogenously distributed in the matrix.
Figure 10. Backscattered image (CP) taken from the Al-Mg-Si alloy sample (as-cast condition) with Ag addition (f) and the corresponding x-ray images of Ag, Fe, Si, Al and Cu (a–e). The AlFeSiAgCu rich intermetallic phase particle observed in microstructure of the high Ag containing AA6063 alloy.

Figure 11. Mechanical Properties of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe using non-preheated metallic mold (MM) casting.
Hardness of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe using preheated graphite mold (GM) casting at 650 °C

Table 3. ASTM Grain Size measurement of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe.

| Alloy code               | ASTM grain size number, G | Mean intercept length(μm) |
|-------------------------|---------------------------|---------------------------|
| As cast                 |                           |                           |
| Base                    | 11.90 ± 0.15              | 5.19 ± 0.27               |
| Base + Ag               | 12.56 ± 0.14              | 4.12 ± 0.21               |
| Base + Ag + Zn          | 12.33 ± 0.06              | 4.45 ± 0.09               |
| Base + Ag + Fe          | 12.36 ± 0.027             | 4.41 ± 0.04               |

Table 4. Fe-intermetallic phases(s) particle of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe.

| Alloy code               | Size            | Shape descriptors | percent surface fraction, %SF |
|-------------------------|-----------------|-------------------|-----------------------------|
|                         | Mean            |                  |                             |
| Base                    | 0.474           | 2.614             | 0.840 1.71 0.792 0.891 1.814 ± 0.81 |
| Base + Ag               | 2.410           | 9.348             | 0.299 1.60 0.290 0.200 0.720 ± 0.37 |
| Base + Ag + Zn          | 0.009           | 0.275             | 0.026 1.00 0.05 0.19 0.237 ± 0.05 |
| Base + Ag + Fe          | 35.35           | 131.24            | 1.00 20.28 1.00 1.00 2.278 ± 0.00 |
|                         | 1.33            | 2.04              | 0.934 1.565 0.747 0.931 2.278 ± 0.00 |
|                         | 10.22           | 11.01             | 0.169 0.729 0.255 0.112 0.720 ± 0.00 |
|                         | 0.009           | 0.275             | 0.10 1.00 0.211 0.398 0.237 ± 0.05 |
|                         | 104.4           | 113.4             | 1.00 4.73 1.00 1.00 2.02 ± 0.72 |
|                         | 0.334           | 1.7               | 0.864 1.566 0.765 0.905 2.02 ± 0.72 |
|                         | 0.93            | 3.7               | 0.237 0.87 0.267 0.147 0.237 ± 0.05 |
|                         | 0.009           | 0.275             | 0.08 1 0.13 0.48 0.237 ± 0.05 |
|                         | 7.09            | 32.1              | 7.64 1 1 1 1 1 4.16 ± 1.2 |
|                         | 1.6             | 3.82              | 0.874 1.72 0.68 0.867 4.16 ± 1.2 |
|                         | 10              | 10.76             | 0.2 1.13 0.2 0.113 0.237 ± 0.05 |
|                         | 0.06            | 0.453             | 0.037 1 0.026 0.253 0.237 ± 0.05 |
|                         | 317.6           | 215.6             | 37.75 1 1 1 1 1 4.16 ± 1.2 |
along the Al matrix grain boundaries resulting in removing the precipitate free zone and improving corrosion resistance.

Table 5. Mg2Si particle characteristics of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe.

| Particle Characteristics | Size | Shape descriptors |
|--------------------------|------|-------------------|
|                         | Area, A | Perimeter, P | Circularity, C | Aspect ratio, AR | Roundness, R | Solidity, S | %SF |
| **Alloy Code** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** | **Mean** | **SD** | **Min** | **Max** |
| **Base** | 0.073 | 0.493 | 0.004 | 14.68 | 0.941 | 0.130 | 0.144 | 1.00 | 0.742 | 0.66 | 1.00 | 0.742 | 0.0225 | ± 0.17 |
| **Base + Ag** | 0.912 | 3.04 | 0.009 | 20.9 | 2.72 | 5.49 | 0.248 | 1.00 | 0.829 | 2.256 | 0.632 | 0.888 | 0.851 | ± 0.0 |
| **Base + Ag + Zn** | 0.257 | 2.05 | 0.009 | 37.68 | 1.024 | 3.547 | 0.194 | 1.00 | 0.919 | 1.482 | 0.794 | 0.935 | 0.43 | ± 0.1 |
| **Base + Ag + Fe** | 0.817 | 2.254 | 0.009 | 11.509 | 4.1 | 9.05 | 0.326 | 1.00 | 0.744 | 3.164 | 0.616 | 0.843 | 1.22 | ± 0.17 |

Figure 13. Fracture surface taken from as-cast AA6063 base alloy (a), base alloy plus high Ag and low Fe, (b), base alloy plus high Ag and Zn and low Fe (c), and base alloy plus high Ag and Fe (d) at solidification cooling rates of 0.65, 0.714 °C s⁻¹, 0.647 °C s⁻¹ and 0.65 °C s⁻¹ respectively. The presence of α-Al dendrite phase are observed in all micrographs (a-d), while a discontinuous precipitate particle and a micro crack and grain boundaries voids in (c) and (d) are observed, respectively. A mixed of dimples and dendritic structure fracture are dominant in (a), (b) and (c), however micro cracks and voids are observed in (d).
Table 6. Wear resistance of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe.

| Sample       | Weight loss, g | Sliding distance, m | Wear rate (kg/m)       | Wear rate (mm³/m) | Frictional Force, N | Coefficient of friction |
|--------------|----------------|---------------------|------------------------|-------------------|---------------------|------------------------|
| Base         | 0.193          | 376.8               | 5.12E-07 ± 4.75E-09    | 0.190 ± 0.0018    | 3.3                 | 0.165                  |
| Base + Ag    | 0.109          | 376.8               | 2.89E-07 ± 3.46E-09    | 0.108 ± 0.0013    | 3.34                | 0.167                  |
| Base + Ag + Zn | 0.106       | 376.8               | 2.81E-07 ± 3.94E-09    | 0.105 ± 0.0015    | 3.2                 | 0.166                  |
| Base + Ag + Fe | 0.107      | 376.8               | 2.84E-07 ± 4.20E-09    | 0.106 ± 0.0016    | 3.3                 | 0.165                  |

Normal Load = 20 N, speed = 150 rpm, time = 10 min, disk diameter = 100 mm and contact disk diameter = 80 mm.
4. Conclusions

Solidification data are obtained for AA6063 alloy with added Ag at low and high level of Fe content by using thermal analysis technique. Microstructural evolution, hardness, mechanical properties, wear and corrosion behavior of AA6063 aluminum alloy casting are investigated and the following conclusions are achieved:

1. Fe-intermetallic phases such as Al9.58Si0.31Fe0.97Mn0.03Ag0.06 or Al14Si0.56FeCu3Ni0.68, Al15.55Si0.37Ag0.13Cu0.1 (Fe0.94Mn0.06), and Al7.97SiFe1.16Ag0.029 phases are detected in the microstructure of AA6063 alloy with added Ag at low and high level of Fe content.

2. The formed AlFeSi intermetallic (Al15.55Si0.37Ag0.13Cu0.1 (Fe0.94Mn0.06), Al7.97SiFe1.16Ag0.029), and the Mg2Si phase particles are homogenously distributed along the Al matrix grain boundaries resulting in removing the precipitate free zone and improving wear and corrosion resistance for AA6063 alloy casting with of Ag addition at low and high level of Fe-content or at high Zn content.

3. The Ag have some refining and modification effect on the AlFeSi-intermetallic and Mg2Si phase particles formed during the solidification of the AA6063 aluminum casting at low Fe levels. This refining and modification effect increase with added high Zn and low Fe content. A decrease of the grain size and aspect

Figure 14. Wear resistance or Weight loss of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe using preheated graphite mold casting at 650 °C.
ratio and 2% volume fractions are obtained with added Zn and Ag (0.8 wt%Ag or Zn) at low Fe content (0.25 wt%Fe). Moreover, an increase in their shape descriptors (i.e. circularity, roundness and solidity) obtained.

4. Hardness and strength increase with the high Ag and Zn addition at low Fe content. This can be explained due to the refining and modification of AlFeSi-intermetallic and Mg2Si phase particles formed during the solidification of the AA6063 aluminum casting obtained by Ag and Zn addition at low Fe levels. However, the decrease in percent elongation at high Fe content is related to the micro crack formation and grain boundary voids.

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Author Contributions

This paper was a shared work between Dr Mahmoud M. Tash and Dr Waleed Khalifa. Dr Tash planned and designed the experimental works, while Dr Khalifa performed the thermal analysis experiments. For the performed tests, Dr Tash made the microstructure analysis, wear and corrosion tests while Dr Khalifa made hardness and mechanical testing. Both of authors shared in analyzed the data and Dr Tash wrote the paper in its final form.

Conflicts of Interest

The authors declare no conflict of interest.

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Figure 16. Potentiodynamic polarization curves of AA6063 base alloy with adding Ag, Ag plus Zn, and Ag plus Fe in 3.5% NaCl solution.
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