Effect of Al$_2$O$_3$ Particles and Precipitation Hardening on the Properties of Cast 332 Aluminum Alloy

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Abstract

In this work, 332 Al alloy was prepared and reinforced with (0.5% and 1%) nano-Al$_2$O$_3$ particles. The prepared unreinforced and reinforced 332 Al alloy with nano-Al$_2$O$_3$ were solution heat treated (T6) at 510°C and aged at 225°C with different times (1, 3, and 5 h). Hardness test was performed on all the prepared alloys. All prepared alloys were dry slided under different applied loads (5, 10, 15, and 20 N) against steel counterface surface using pin on disk apparatus. The results showed that refinement effect was observed after addition of nano-Al$_2$O$_3$ particles and a change in silicon morphology after performing the solution heat treatment. The results also showed that hardness was increased and the wear rate decreased with increasing the nano-Al$_2$O$_3$ particles in the matrix of 332 Al-Alloy.

Keywords: 332Alloy, hardness, nano Al203, T6 heat-treatment, wear rate.

1. Introduction

The distinct combination of properties delivered by Al and Al-alloys make aluminum one of the most flexible, cost-effective, and striking metallic materials for a wide range of applications from soft, very ductile wrapping foil to the most exigent applications in engineering. They are employed in the automotive industry, aerospace industry, in construction of machines and many other applications [1]. The most important reason for alloying is to increase strength, hardness, and resistance to wear and other mechanical properties. The most common alloying elements in Al-Si alloys that provide increased strength particularly when combined with heat treatment, are copper, magnesium, manganese, silicon, and zinc. The solid solubility of these elements in aluminum is significant, and in all cases the solubility increases with increasing temperature [1, 2].

Aluminum piston alloys are an important group of industrial aluminum alloys that have good mechanical properties at raised temperatures. At the same time, these alloys are resistant to sudden changes in temperature [3]. Many aluminum alloys, reinforced with ceramic particles have been investigated extensively. Several researchers showed that the presence of ceramic reinforcing particles in the aluminum alloy matrix help with improving its strength. There was also a notable improvement in the resistance for wear with increase of addition of ceramic particles especially when combining with heat treatment [4 - 6]. S. Shivkumar et al. (1990) [7] studied the effect of solution heat treatment parameters on tensile properties of cast 356.2 aluminum alloys. They found that increasing the solution treatment temperature has an advantageous effect on the mechanical properties attainable after heat treatment. While M. Kok (2005) [8] fabricated the 2024 Al alloy and reinforced it with Al$_2$O$_3$ particles by stir casting technique and studied its mechanical properties. They found that the bonding between Al alloy and Al$_2$O$_3$ particles and the wettability were improved.
M. Kok and K. Ozdin (2006) [9] investigated the effect of $\text{Al}_2\text{O}_3$ particle content on the wear rate of 2024 Al alloy. "They found that the wear rate of the reinforced 2024 alloy was significantly less than that of the unreinforced 2024 alloy, and decreased with increasing $\text{Al}_2\text{O}_3$ particles content". F. Zainon et al. (2016) [10] studied the effects of heat treatment on the hardness, microstructure and wear of Al-alloy 332. They found that the hardness of the alloy has improved and the wear rate was decreased compared to the as-cast alloy.

In this work, the effect of $\text{Al}_2\text{O}_3$ Nano-particles with two different percentages and precipitation hardening with different aging times on the microstructure, hardness, and wear properties were studied.

### Table 1,
Chemical composition analysis of produced castings.

| Element          | Si %  | Fe %  | Cu %  | Mn %  | Mg %  | Cr %  | Zn %  | Ti %  | Pb %  | Al %  |
|------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| 332 Alloy        | 9.02  | 0.70  | 2.49  | 0.2   | 0.9   | 0.01  | 0.4   | 0.02  | 0.03  | Bal.  |
| 332 Alloy + 0.5% $\text{Al}_2\text{O}_3$ | 9.17  | 0.71  | 2.12  | 0.2   | 0.82  | 0.01  | 0.54  | 0.02  | 0.03  | Bal.  |
| 332 Alloy + 1% $\text{Al}_2\text{O}_3$ | 9.61  | 0.65  | 2.67  | 0.19  | 1.57  | 0.01  | 0.64  | 0.02  | 0.03  | Bal.  |

Fig. 1. some of the prepared alloys (as-cast 332 Al alloys).

After completing the casting process, the aluminum alloys were set for heat treatment. A carbolite furnace is first calibrated using a thermocouple (type k). The first step in heat treatment (T6) is solution heat treatment which is performed at temperature of (510 °C) in which the alloys are kept in furnace for 5 hours. The second step is quenching the alloys with rapid cooling to room temperature by inserting the alloys in water. Finally, the alloys were aged at a temperature of (225 °C) with three different periods (1, 3, and 5 hours). The alloys, after that, were let to cool down to room temperature in air.

The wear test was accomplished in laboratory at the Materials Engineering department/University of Technology using pin on disk apparatus according to the ASTM G99-95 standard. The pin on disk apparatus is composed of a rotating disk (277.4 r.p.m) and a specimen holder connected to a lever at one end and the other to hold the weights. The radius of the sliding track (from the center of the specimen to the center of the disk) is (6 cm) the test is done at loads of (5, 10, 15, 20N) and sliding time of 20 min.

### 3. Results and Discussion

Figure (2) shows the microstructure of the as-cast alloys with different percentages of nano-$\text{Al}_2\text{O}_3$ particles (0%, 0.5%, 1%). It is clear that $\alpha$-Al phase dendrites (light gray), eutectic phase (mixture of $\alpha$-matrix, and fine dark gray Si phases) and some intermetallic phases are presented in the matrix. The micrographs showed that the $\alpha$-Al dendrite size of the reinforced alloy with (0.5% and 1% $\text{Al}_2\text{O}_3$) (figure 2b and c) is smaller than the unreinforced alloy (figure 2a) in which $\alpha$-Al dendrite size decrease with increasing content of nano-$\text{Al}_2\text{O}_3$ particles. The reason can be related to the nano-$\text{Al}_2\text{O}_3$ particles act as nucleation sites. The effect of stirring process is reflected in the
uniformity of the particle distribution. In stir casting an almost uniform distribution of nano-Al$_2$O$_3$ particles can be achieved. In addition to homogenous distribution, with increasing of percentage of nano-Al$_2$O$_3$ particles the microstructure was refined and the hardness of 332 Al alloy is increased.

Fig. 2. microstructure of prepared alloys (a) 332 Al alloy (b) 332 Al alloy with 0.5% Al$_2$O$_3$ (c) 332 Al alloy with 1% Al$_2$O$_3$.

The microstructure of solution heat treated 332 Al alloys reinforced with different nano-Al$_2$O$_3$ percentages is shown in figure (3 a, b, and c). The effect of solution treatment on morphology of eutectic Si is evident in figure (3). This change in morphology of eutectic Si observed after heat treatments for holding time of 5 hours. Eutectic Si without heat treatment is evolved in needle-like form as showed in figure (2). After solution treatment we noted that the platelets were fragmentized into smaller platelets with spherical edges, see figure (3). The smaller Si particles were changed to rounded shape. The spheroidized morphology of the silicon phase is expected to improve the mechanical properties of the Al-Si alloys and make them stronger. Figure (3) also shows that solution heat treatment has great influence on spheroidization of eutectic silicon particles for the reinforced 332 Al alloys with nano-Al$_2$O$_3$ particles than that of the unreinforced 332 Al alloy figure (3 b and c). It is not only decrease the size of eutectic silicon particles, but also enhances greatly the spheroidization degree of eutectic silicon particles for the reinforced 332 Al alloys.
Figure (4 a, b, and c) illustrates the microstructure of the unreinforced 332 Al alloys, 0.5% Al$_2$O$_3$, and 1% Al$_2$O$_3$ reinforced Al alloys respectively. There are two possible combinations of precipitates in these alloys. Precipitation of (Mg$_2$Si) and (CuAl$_2$), or alternatively (Al$_5$Mg$_8$Si$_6$Cu$_2$) and (CuAl$_2$), where the phase (CuAl$_2$) forms if the Cu concentration is high enough. These precipitates are assumed to be unshearable and their contribution to strength is modelled via looping mechanism of Ashby and Orowan [11]. Strengthening is obtained due to formation of dislocation loops around the precipitates that have attained a critical size, and therefore can no longer be sheared by gliding dislocation. Precipitation hardening of the 332 alloys after aging occurs in the matrix saturated with Si, Cu, and Mg in solid solution. The hardening mechanism suggests the formation of GP zones in the early stage of aging, and this is followed by the precipitation of $\theta''$ and $\theta'$. At long aging time, overaging occurs and the hardness drops due to extensive aging when the precipitation turns the equilibrium phase $\theta$. The hardness drop is due to long mean free path between the $\theta$ precipitates. The coarsening of the precipitates and the reduced density at longer aging times, widen the inter-particle spacing and facilitate the dislocation motion through the metal matrix.
Figure (5) shows the relationship between hardness and weight percentage of nano-Al$_2$O$_3$ particles for the as-cast 332 Al alloys. It is clear from this figure that the incorporation of nano-Al$_2$O$_3$ particles in aluminum matrix causes reasonable increase in hardness. This increase in hardness value is due to grain refinement of Al-matrix, and the role of uniform distribution of nano-particles as obstacles to the dislocations motion according to Orowan mechanism [12]. The increased hardness can be attributed also to the contribution of metallurgical composition. The hardness is also increased with increasing the percentage of nano-Al$_2$O$_3$ particles. The higher hardness (in as cast state) is obtained for the 332 Al alloy with 1wt% Al$_2$O$_3$ as can be seen in figure (5).

The results of hardness test showed that the solution heat treatment and aging increased the hardness value as shown in figures (5), and (6). The higher hardness value was obtained at the aging time of 3 hrs. for the unreinforced and reinforced alloys. It is also observed that with an aging time of 5 hrs. overaging is achieved. This lead to decrease the hardness as compared with that at 3 hrs.
The wear behavior of the as cast 332 aluminum alloys has been studied before and after the addition of the reinforcing Nano-Al2O3 particles. Also the study included the alloys after performing solution heat treatment and aging. The pin on disk method was employed for all the specimens cut from alloys at different states (as cast and aged alloys) taking into account the effect of applied load on wear rate.

The as cast 332 Al alloys before and after reinforcement material addition (Nano-Al2O3 particles) were studied through plotting the relationship between load and wear rate as in figure (7). It is obvious that the wear rate of the as cast 332 Al alloys increases with the increase in applied load. It is clear from the figure that the wear rate initially increases slowly with increase in applied load irrespective of the as-cast 332 Al alloy type and at a later stage beyond certain applied load, the wear rate rises up. The load at which wear rate increases suddenly is termed as transition load which in most of the alloys tested was (15N). Figure (7) shows that the addition of nano-Al2O3 particles led to an improvement in wear resistance of 332 Al alloy. In the 332 Al alloys reinforced with nano-Al2O3 particles, material removal is delayed because the distribution of nano-Al2O3 particles in the 332 Al alloys during dry sliding. The hard Al2O3 particles effectively resist the micro cutting action of counterface asperities and resist also the applied load. It is clear that Al2O3 particles have considerably increased the hardness of the 332 matrix alloy. The decrease in the wear rate is related to the hardening effect of Al2O3 Nano particles in the as cast condition, and due to both Al2O3 Nano-particles and precipitation hardening effects in solution heat treated and aged condition.

This enhancement in wear properties results can be ascribed to the improvement of alloy hardness due to the reinforcing particle addition (Nano-Al2O3), precipitation hardening and may be related to spheroidization of silicon particles as a result of solution heat treatment. The lowest wear rate of the alloys observed was for 332 Al alloy with 1% Al2O3 nano particles in both states, as cast and precipitation hardened, see figure (8).

4. Conclusions

1. The addition of nano-Al2O3 particles affect the α-Al phase size which has been decreased with increasing the percentage of the nano-particles.
2. Nano-Al2O3 particles addition increased the hardness of 332 Al alloy in which the hardness increases with increasing the nano-Al2O3 particles content. This is related to the nano-

Fig. 6. the hardness of 332 Al alloys at different ageing times.

Fig. 7. the effect of applied load on the wear rate at sliding time of 20 min as-cast 332 Al alloys.

Fig. 8. the effect of load on the wear rate of aged 332 Al alloy with 1% Al2O3 Nano particles with different times at sliding time of 20 min.
particles that act as barriers to dislocations motion. The results showed that the hardness increased with Al2O3 additions, it reached to (92 kg/mm2) when adding 1 wt.% Al2O3, but after reinforcing and aging for 3 hrs. the hardness reached to (120 kg/mm2).

3. The nano-Al2O3 particles addition resulted in decreasing the wear rate of the 332 Al alloys as the addition increases.

4. The solution heat treatment and aging has a significant effect on the eutectic silicon morphology in which the shape changed after solution heat treatment from large platelets into small platelets with rounded edges. This change in silicon morphology improved the hardness and wear resistance.

5. Delamination is found to be the dominant wear mechanism in all 332 Al alloys tested during dry sliding test.

5. References

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تأثير دقائق 


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الخلاصة

في هذا البحث تم تحضير سبيكة آلمنيوم 332، مقواة بدقائق أوكسيد الالمنيوم النانوية (Al2O3) (Solution heat treatment) 50 نانومتر، ونسبة مختلفة (5، 10، 15، 20، 100%)، ونسبة مختلفة (5، 10، 15، 20، 100%). تم إجراء عملية المعالجة الحداثية (Solution heat treatment-T6) عند درجة حرارة (510 °C) وتم إجراء عملية المعالجة الحداثية (Solution heat treatment) عند درجة حرارة (225 °C) وتحت أحمال مختلفة (5، 10، 15، 20، 100%).

لدراسة سلوك السبيكة أجرت عينة السبيكة المعالجة (Solution heat treatment) تحت نتائج تدل على تأثير تتغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون، وكذلك حدث تغير في شكل طور السيليكون.