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 ℃ and aged at 225 ℃ 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 effect1of Al_2O_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 Al_2O_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 Al_2O_3 Nano-particles with two different percentages and precipitation hardening with different aging times on the microstructure, hardness, and wear properties were studied.

2. Experimental Procedure

Master alloys of (Al-Cu, Al-Mg, Al-Zn, and pure Al) brought from the local market and (Al-12%Si) provided by the General Company for Electrical Industries in Baghdad were used as a starting materials to prepare the reference alloy (332). The stirring process was carried out by inserting the stirrer into the crucible while it is inside the furnace. The stirring continued for 5 minutes, in which the crucible was left inside furnace to preserve the solubility. The molten alloy was also stirred just before pouring into the mold cavity. The chemical compositions of the produced castings are shown in table (1). Some of the prepared castings are illustrated in figure (1).

Table 1,
Chemical composition analysis of produced castings.

Element	Si %	Fe %	Cu %	Mn %	Mg %	Cr %	Zn %	Ti %	Pb %	Al %
332 Alloy	9.02	0.7	2.49	0.2	0.9	0.01	0.4	0.02	0.03	Bal.
332 Alloy + 0.5% Al_2O_3	9.17	0.71	2.12	0.2	0.82	0.01	0.54	0.02	0.03	Bal.
332 Alloy + 1% Al_2O_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 ºC) 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 ºC) 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-Al_2O_3 particles (0%, 0.5%, 1%). It is clear that α-Al phase dendrites (light gray), eutectic phase (mixture of α-matrix, and fine dark gray Si phases) and some intermetallic phases are presented in the matrix. The micrographs showed that the α-Al dendrite size of the reinforced alloy with (0.5% and 1% Al_2O_3) (figure 2b and c) is smaller than the unreinforced alloy (figure 2a) in which α- Al dendrite size decrease with increasing content of nano-Al_2O_3 particles. The reason can be related to the nano-Al_2O_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_2O_3 particles can be achieved. In addition to homogenous distribution, with increasing of

percentage of nano-Al_2O_3 particles the microstructure was refined and the hardness of 332 Al alloy is increased.
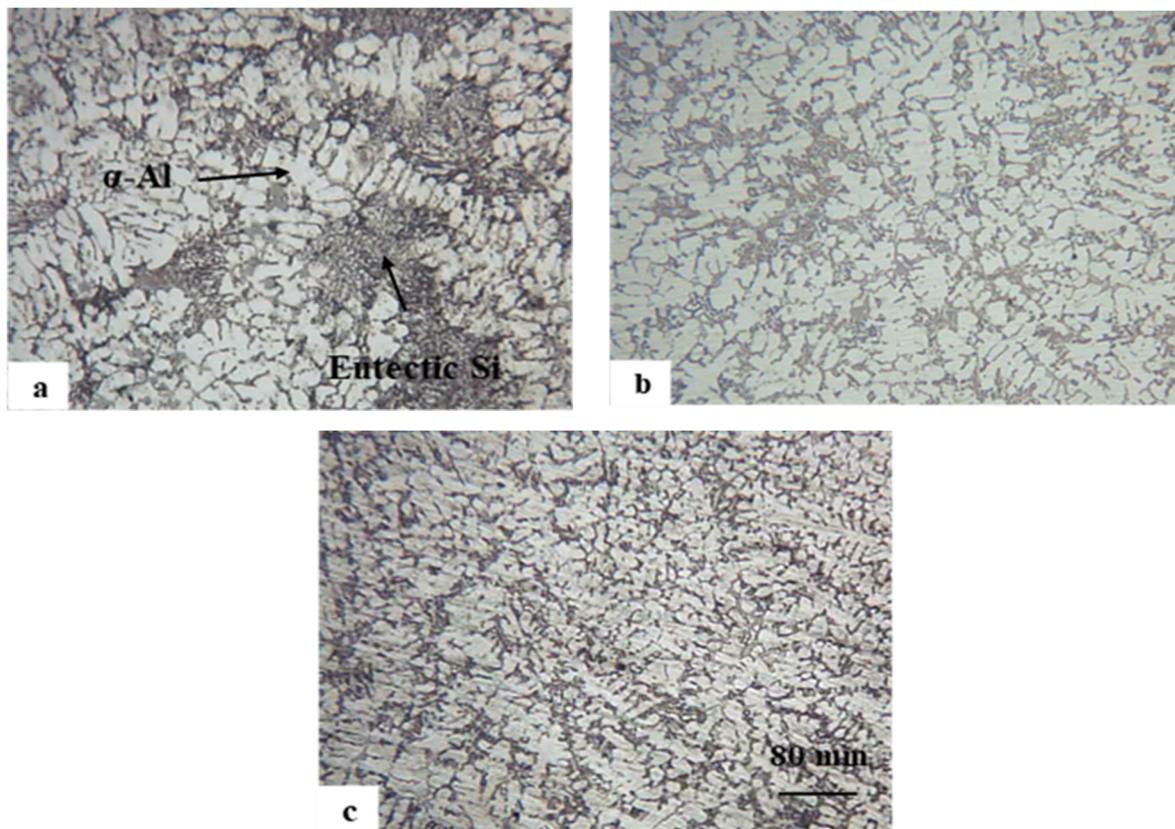
Fig. 2. microstructure of prepared alloys (a) 332 Al alloy (b) 332 Al alloy with 0.5% Al_2O_3 (c) 332 Al alloy with 1% Al_2O_3.

The microstructure of solution heat treated 332 Al alloys reinforced with different nano-Al_2O_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_2O_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
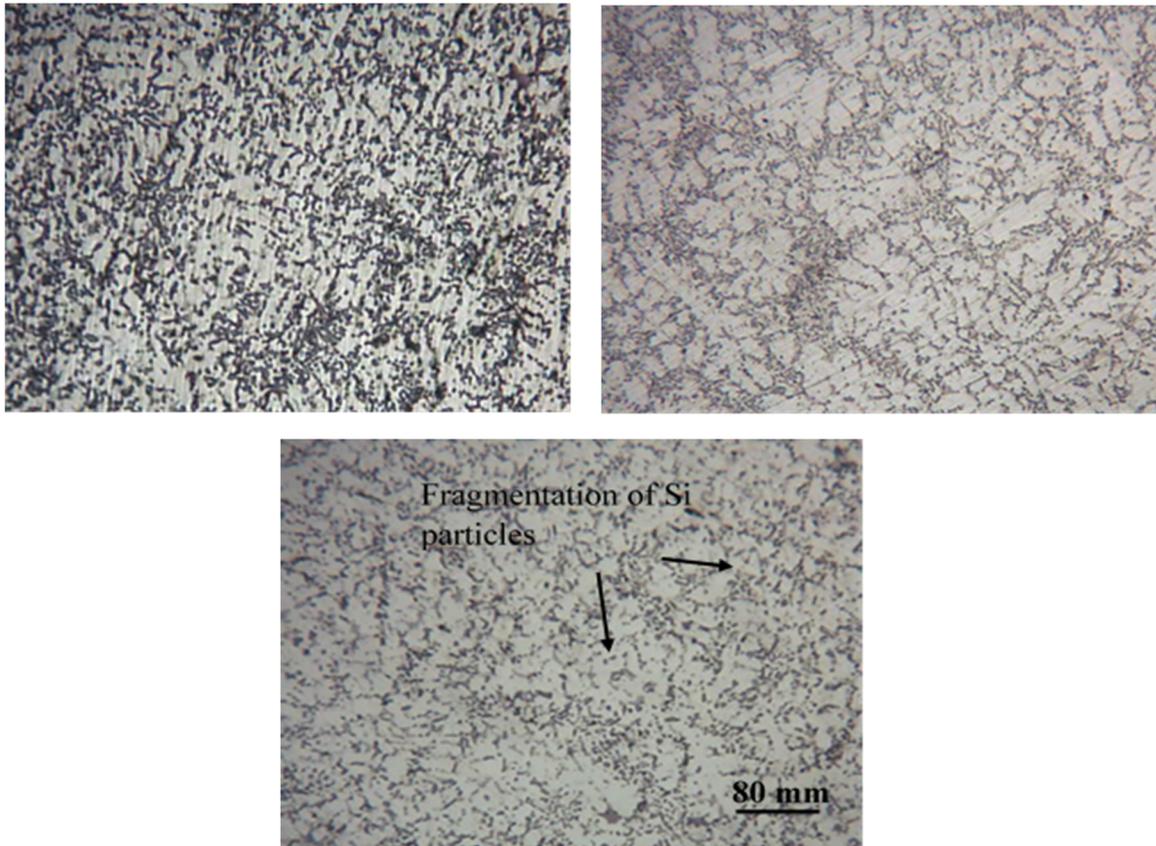
Fig. 3. microstructure of solution heat treated 332 Al alloys (a) 332 Al alloy (b) 332 Al alloy with 0.5% Al₂O₃ (c) 332 Al alloy with 1% Al₂O₃.

Figure (4 a, b, and c) illustrates the microstructure of the unreinforced 332 Al alloys, 0.5% Al_2O_3, and 1% Al_2O_3 reinforced Al alloys respectively. There are two possible combinations of precipitates in these alloys. Precipitation of (Mg_2Si) and ($CuAl_2$), or alternatively ($Al5Mg8Si6Cu2$) 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 θ'' and θ'. At long aging time, overaging occurs and the hardness drops due to extensive aging when the precipitation turns the equilibrium phase θ. The hardness drop is due to long mean free path between the θ 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.
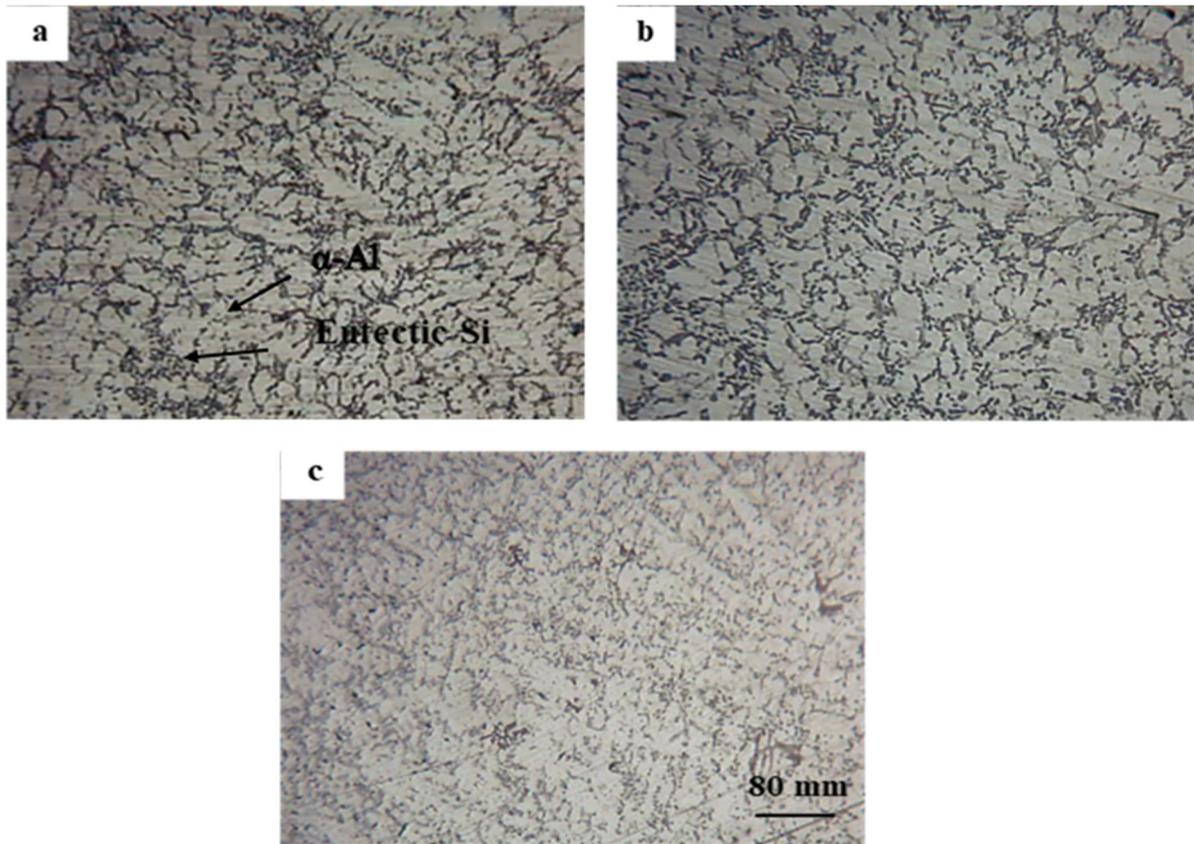
Fig. 4. microstructure of aged 332 Al alloys at time of (3hrs) (a) unreinforced 332 Al alloy (b) 332 Al alloy with 0.5% Al₂O₃ (c) 332 Al alloy with 1% Al₂O₃.

Figure (5) shows the relationship between hardness and weight percentage of nano-Al_2O_3 particles for the as-cast 332 Al alloys. It is clear from this figure that the incorporation of nano-Al_2O_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_2O_3 particles. The higher hardness (in as cast state) is obtained for the 332 Al alloy with 1wt% Al_2O_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.
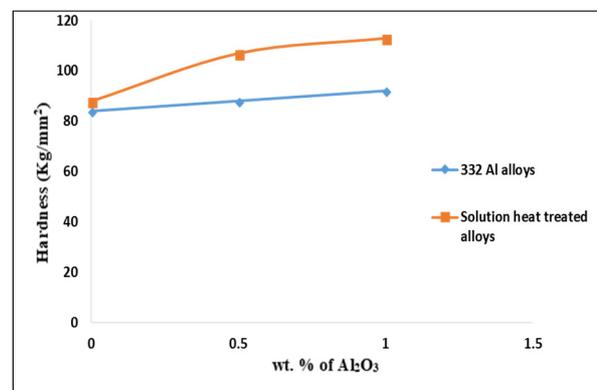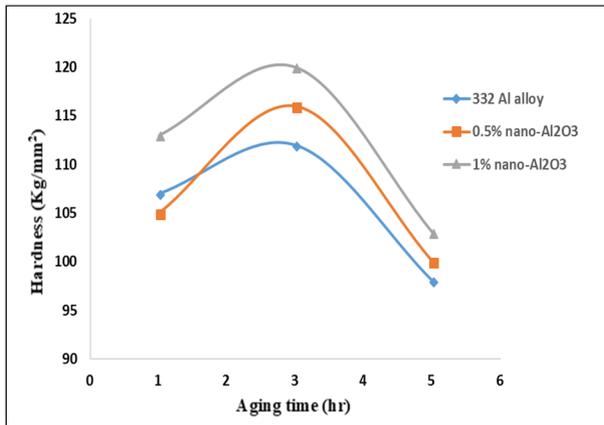

Fig. 5. the hardness of as-cast and solution heat treated 332 Al alloys at different weight percentages of nano-Al₂O₃ particles.

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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.**

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.
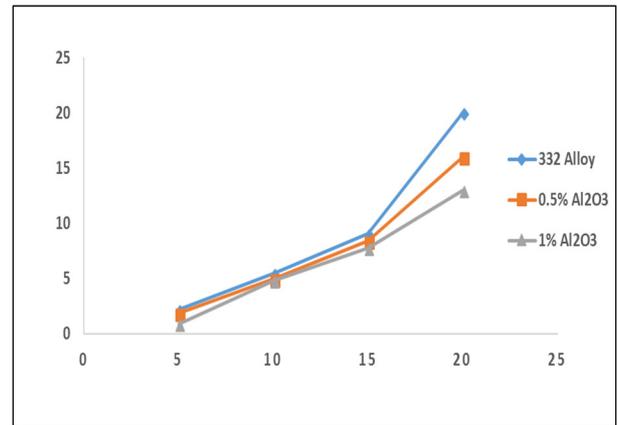
This enhancement in wear properties results can be ascribed to the improvement of alloy hardness due to the reinforcing particle addition (Nano-Al_2O_3), precipitation hardening and may be related to spheroidization of silicon particles as a result of solution heat treatment. The lowest wear rate of the alloys observed was for 332 Al alloy with 1% Al_2O_3 nano particles in both states, as cast and precipitation hardened, see figure (8).
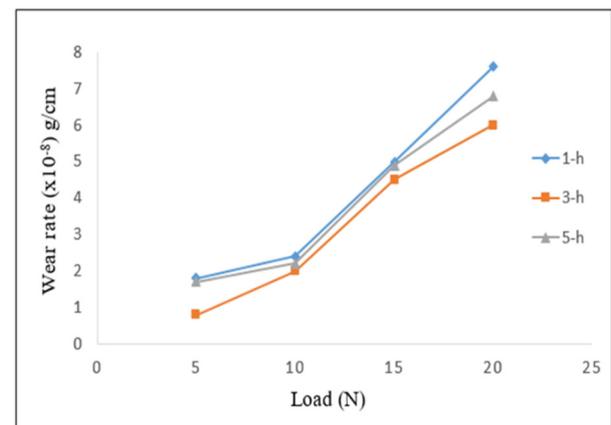
Fig. 8. the effect of load on the wear rate of aged 332 Al alloy with 1% Al_2O_3 Nano particles with different times at sliding time of 20 min.

4. Conclusions

1. The addition of nano-Al_2O_3 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-

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 Al₂O₃ وعملية التصليد بالترسيب على خواص سبيكة الالمينيوم ٣٣٢

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الخلاصة

في هذا البحث تم تحضير سبيكة ألمينيوم 332، مقواة بدقائق أوكسيد الالمينيوم النانوية (Al_2O_3) بحجم (50 nm) وبنسب مختلفة (٥,٠% و ١%). تم إجراء عملية المعاملة الحراية المحلولية (Solution heat treatment-T6) لجميع سبائك الألمينيوم ٣٣٢ المقواة وغير المقواة بدقائق أوكسيد الألمينيوم النانوية (Al_2O_3)، عند درجة حرارة ($510^{\circ}C$) وكذلك تم إجراء عملية التعتيق عند درجة حرارة ($225^{\circ}C$) وعند ثلاث فترات زمنية مختلفة (١، ٣، ٥ ساعة). تم إجراء فحص الصلادة لجميع السبائك المحضرة. تم اختبار جميع السبائك المحضرة بوساطة جهاز البلى الإنزلاقي ذي نظام المسمار على القرص (Pin on Disk) لدراسة سلوك البلى الجاف لسبائك الألمينيوم المحضرة وذلك على قرص من الفولاذ المصلد تحت أحمال مختلفة (5، 10، 15، 20 نيوتن). لوحظ حدوث تنعيم في الحجم الحبيبي بعد إضافة دقائق (Al_2O_3) النانوية وكذلك حدوث تغير في شكل طور السيليكون بعد إجراء عملية المعاملة الحرارية المحلولية (Solution heat treatment). كما أوضحت النتائج زيادة الصلادة و انخفاض معدل البلى مع زيادة نسبة إضافة دقائق (Al_2O_3) في ارضية السبيكة ٣٣٢.