Influence of Boron Addition and Heat Treatment on the Mechanical Properties of 7050 Al Alloy

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Abstract:

In this study, the effect of boron content as a grain refiner on the structural and the mechanical properties of 7050 aluminum alloy was investigated. Three different amount of boron was selected as 1.5, 2.5 and 3.5 wt.%B with two different holding time (H.T) for boron in the furnace before pouring the cast, 20 and 30min. The results revealed that the addition of boron highly affected the grain size structure changed the dendritic structure of the as-cast alloys into the equiaxed structure. Solution heat treatment was carried out to all samples before tensile testing. Significant improvement in the ultimate tensile stress (UTS) was obtained with the addition of boron contents after 30min holding time compared with solution heat-treated specimen. While decreasing the holding time to 20min after the boron addition has an adverse effect on the UTS. The highest UTS was obtained in the solution treated sample with 1.5% boron at 30min holding time. The impact test showed that the sample contains 2.5%B at 30min H.T exhibit the highest absorbed energy because of the coarse microstructure obtained. The hardness was measured after solution treatment and the maximum hardness obtained for the samples of 1.5%B at 30min H.T and 3.5%B at 30min H.T due to precipitation hardening. After the solution treatment, the samples were aged at 180^{o}C for the different aging time between 0.5 and 4.0 hours, followed by water quenching and then the hardness was measured. The results revealed that the maximum hardness of 135Hv obtained for the sample with 2.5%B at 20 min H.T after aging for 3hr. Finally, it was deduced an excellent correlation between the addition of boron at different holding time before pouring and the microstructure and the hardening of 7050 aluminum alloy at different times. These results in a good agreement with the results of impact and tensile tests.

Keywords: heat treatment, Boron, grain refiner, 7050 Al alloys, precipitation hardening, mechanical properties

1. Introduction

Aluminum alloys are used as structural materials in the aerospace and the automotive industries, which need a continuous improvement in the mechanical properties of these alloys [1]. The 7xxx (Al-Zn-Mg-Cu) series are the most common aluminum alloys used in aerospace applications due to the high specific strength and other good mechanical properties[2–4]. The mechanical properties of the 7xxx are influenced by the chemical composition and the microstructure features. There are many microstructural features that affect the mechanical properties of the 7xxx series. The 7xxx alloys are heat treated and aged to improve the mechanical properties significantly [5–7], 7050 Aluminum alloy characterized by high strength, good toughness and good stress corrosion crack resistance [8]. The usual precipitation sequence of 7xxx series Al alloys during aging can be summarized as Supper Saturated Solid Solution (SSSS) → GP zones (GPZs) → metastable η′→ stable η (MgZn2). GPZs and η′ phase are the main precipitation phases responsible for the hardening of the 7050 aluminum alloy.

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Grain refinement has a crucial role in the improvement of the mechanical properties of aluminum and aluminum alloys. The grain refinement could be achieved either by the addition of chemical grain refiner such as Al-5Ti-B or Al–5Zr [9–12]. Otherwise through using of external physical fields during or prior to solidification [13–18]. The effectiveness of Al–5Ti–1B as a grain refinement of Al alloys can be attributed for increasing the potency of TiB_2 particles by the formation of Al_3Ti 2DC during the grain refiner production [19]. It has been postulated that Al–5Ti–1B master alloy is more efficient than Al–5Zr in the grain refinement of aluminum alloys. Furthermore the hardness, strength, and elongation, improved through grain refining by 1 wt.% Al–5Ti–1B and T6 heat treatment [20]. It was found that Al–5Ti–0.75B–0.2C exhibits master alloy a slight grain refining performance more than Al–5Ti–1B master alloy, which represents more improvement on the mechanical properties of pure aluminum [21]. In aluminum alloys, the equiaxed and fine-grained microstructure can be attained by adding heterogeneous nucleation sites into the molten cast. $TiAl_3$, TiB_2 and TiC particles as heterogeneous nucleation sites are provided by the presence of Al-Ti-B and Al-Ti-C grain refiners in the melt. TiB_2 phases in Al-Ti-B refiners are stable, which lead to more efficient grain refinement in aluminum alloys [22].

The heterogeneity in the microstructure and severe segregation of second phases are due to the high content of alloying elements. The mechanical properties of casting products vary according to the location due to the variation of the grain size, the number of eutectic phases and precipitates. Many investigations have been made to eliminate the segregation of the alloying elements during solidification period of Al alloys [23–26]. There are many investigations discussed the effects of aluminum master alloys containing Ti and B on the microstructure and the mechanical properties of aluminum alloys. However, the influence of the holding time for the grain refiner in the furnace after the addition to the molten alloy and before pouring has been rarely reported. The scope of the present work is to study the effect of boron addition, holding time and heat treatment on the mechanical properties and the microstructure of 7050 Al alloy. Microstructures obtained by different heat treatment conditions were investigated by optical microscopy (OM). The influence of the structural refining on the tensile properties and the hardness of this alloy was investigated. Vickers hardness measurements obtained from a hardness tester, a 5kg load was used and each reported value is the average of five measurements.

2. Materials and methods

Aluminum 7050 was used in this study, seven different castings are prepared with the chemical compositions and the specifications shown in Table.1. The castings designed to have the same chemical composition of 2.5% Cu, 6% Zn, and 2.5%Mg. The difference between these castings is the added boron content to the molten metal.

The casting process was performed in electrical resistance furnace. First of all, commercially pure Al (99.999%) was melted in the furnace at 730 ^{o}C using a ceramic crucible then the slag was cleaned. Then pure Zn and Cu as Al-Cu (50/50) were added with stirring to the molten Al respectively. After few minutes of adding Zn and Cu, pure Mg was added on to the melt. After that, the temperature of the furnace was held at 730^{o}C then Boron was added and the holding time was observed after the addition of Boron. After the required holding time, the molten cast is poured into a permanent mold and removed after complete solidification.

The samples used in this study had been divided into two groups. The first group was studied in the as-cast condition and the second group investigated after solution treatment and aging. The samples in the second group were solution heat treated at 480^{o}C for 30 minutes followed by water quenching. The solution heat-treated samples then aged at 160^{o}C for the different aging time between 0.5 and 4.0 hours, followed by water quenching.

The Samples used for microstructural observations were prepared using grinding papers of different grades (from 320 to 1200), then polished by using alumina polishing solution of 0.1 microns with a concentration of 10% alumina in water. The polished samples then were etched by using a solution of hydrofluoric acid and water (0.5% HF). Finally, The Microstructures of as-cast, solution treated and aged samples were investigated using an optical microscope.

The tensile test was carried out on an AG-1000KNG universal testing machine. Cylindrical tensile specimens with gauge length 20mm gauge and diameter of 5mm. Impact test was performed using universal Charpy impact test. Impact test specimens with dimension (55mm x10mm x 10mm) without a notch was used since these alloys expected to be very brittle. The hardness of each sample was determined by Vickers hardness tester with load of 5kg and load duration time of 30 second.

Table 1. Chemical composition of 7050 Al alloy at different specifications

Sample No.	Condition	Chemical Composition wt.%			
		Mg	Cu	Zn	Al
S0	Without B	2.655	3.14	6.182	Bal.
S1	1.5% B - 20 min H.T	2.566	3.15	6.130	Bal.
S2	2.5% B - 20 min H.T	2.673	3.17	6.152	Bal.
S3	3.5% B - 20 min H.T	2.641	3.23	6.231	Bal.
S4	1.5% B - 30 min H.T	2.614	3.11	6.244	Bal.
S5	2.5% B - 30 min H.T	2.681	3.17	6.351	Bal.
S6	3.5% B - 30 min H.T	2.699	3.19	6.390	Bal.

3. Result and discussion

3.1 Effect of boron addition on the as-cast 7050Al alloy

3.1.1 Grain size measurements

The number of grains for the as-cast samples was counted by using Jeffries planimetric method [27]. The number of grains per square millimeter at 100X magnification was calculated using equation (1). Where NA is the number of grains/mm^2, the value of *f* for 100X magnification (M) determined using equation (2). The ASTM grain size (G) was detected by equation (3).

$$N_A = f\left(n_1 + \frac{n_2}{2}\right) \quad (1)$$

$$f = \frac{M^2}{5000} \quad (2)$$

$$G = [3.322 \log N_A] - 2.95 \quad (3)$$

The number of grains and the ASTM grain size number for the as-cast samples with and without boron content summarized in Table.2. The number of grains per square millimeter versus the samples is shown in Fig.1. It is clearly seen that; the number of grains / mm2 increased with the addition of boron content. The sample contains 3.5%B and 20% holding time revealed the maximum number of grains. Generally, the addition of boron increases the number of grains and also changes the microstructure from dendritic to equiaxed. This means that addition of Boron to 7050Al alloy refine the grains.

Table 2. The ASTM grain size number and number of grains / mm^2 of different 7050 Al alloys with different Boron content and holding time.

Sample No.	Condition	Number of grains / mm2 (NA)	Grain size number (G)
S0	Without B	423	0.048
S1	1.5% B - 20 min H.T	524	0.043
S2	2.5% B - 20 min H.T	428	0.048
S3	3.5% B - 20 min H.T	947	0.032
S4	1.5% B - 30 min H.T	788	0.035
S5	2.5% B - 30 min H.T	534	0.043
S6	3.5% B - 30 min H.T	676	0.038

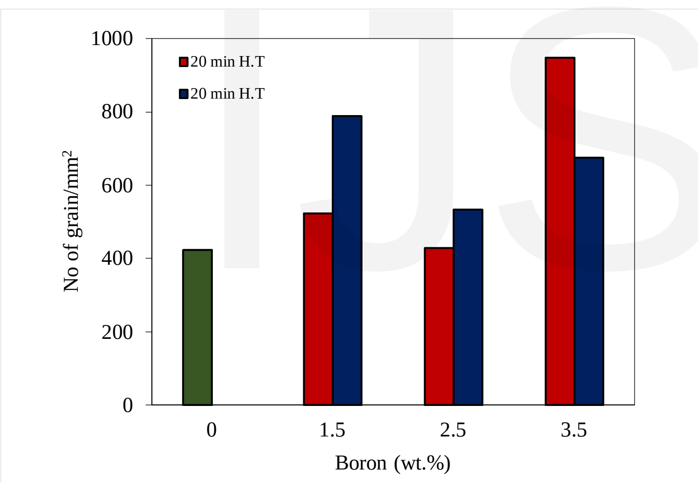

Fig.1 Effect of boron addition and holding time on the grain size of 7050 Al alloys

3.1.2 Microstructure characterization

The microstructure of the as-cast sample without boron addition showed a dendritic structure with little precipitates along the grain boundary as shown in Fig.2a. The microstructure changed from dendritic to the fine equiaxed structure with the precipitates along the grain boundary and inside the grains for the samples with 1.5% and 3.5%B and 20 min holding time before pouring, Fig.2b,d. The difference between the last two samples is that the precipitates are more concentrated around the grain boundary in the sample with 3.5%B as shown in Fig.2d. On the other hand, the microstructure obtained with the addition of 2.5%B and 20 min holding time is coarser than the microstructure obtained in the other two samples with different boron content and same holding time, Fig.2c.

Fig.3 shows the microstructure of the three samples with different boron content 1.5%, 2.5% and 3.5% and 30 min holding time. The microstructure obtained for the sample that contains 1.5%B is a fine equiaxed microstructure as depicted in Fig.3a. This microstructure is similar to the microstructure obtained at 3.5% B and 20 min holding time but the shape of precipitates around the grain boundary is different. The precipitates in Fig.2d are denser and seem to be a continuous network around the grain boundaries. With increasing the boron content to 2.5%, the microstructure is also equiaxed structure but coarser than that obtained with 1.5%B as shown in Fig.3b. Also, the precipitates are different along the grain boundary between the two samples, especially along the grain boundary. The precipitates for the sample of 2.5%B look like discontinues network. Increasing the boron content to 3.5% at 30 min leads to a pronounced decrease in the grain size. Fig.3c shows a fine equiaxed structure with different precipitates along the grain boundary and inside the grains.

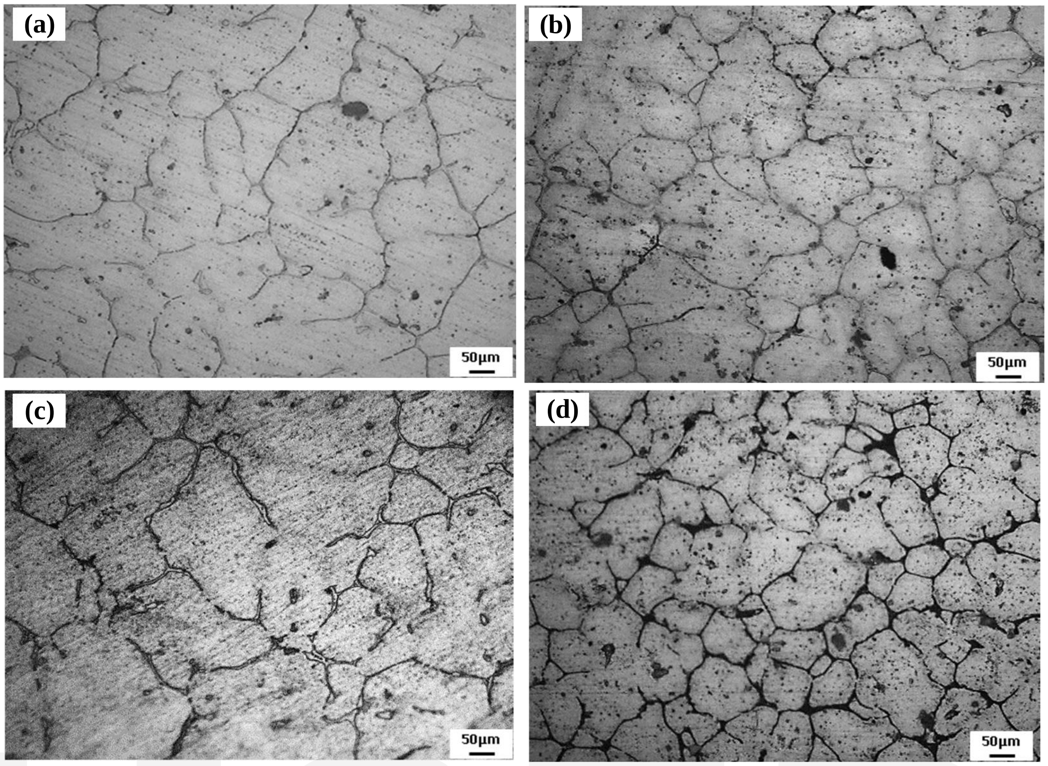

Fig.2 Microstructure of as-cast 7050 Al alloy (a) without B, (b) 1.5%B, 20min H.T, (c) 2.5%B, 20min H.T, and (d) 3.5%B, 20min H.T

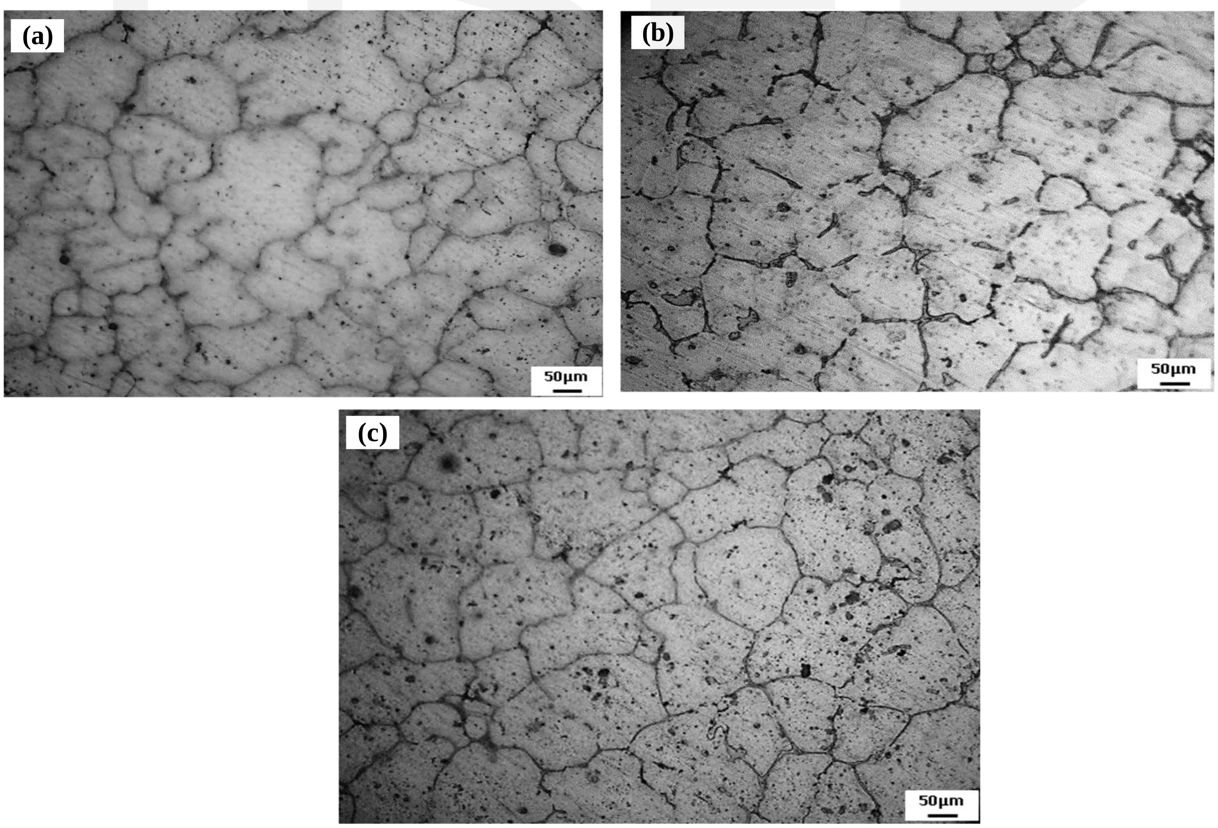

Fig.3 Microstructure of as-cast 7050 Al alloy (a) 1.5%B, 30 min H.T, (b) 2.5%B, 30 min H.T, and (c) 3.5%B, 30 min H.T

3.1.3 Hardness measurements

Hardness was measured for the as-cast samples with and without boron content at different holding times of 20 and 30min. 5 reading were detected for each sample and the average value was calculated. Fig.4 illustrates the effect of the boron content and holding time on the hardening of the as-cast samples. It was expected that the sample with 3.5%B will exhibit the maximum hardness because it has the finest and the smallest microstructure grain size. After comparing the values of the hardness for all specimens it was found that the sample with 2.5%B and 20 min holding time has the highest sample although its microstructure is coarser than the sample with 3.5%B at the same holding time. This may be due to the precipitates that formed in the grain boundary and inside the grains as shown in Fig.2c. In addition, we can conclude that increasing the holding time from 20 to 30 min have decreased the hardness slightly as compared to the as-cast sample.

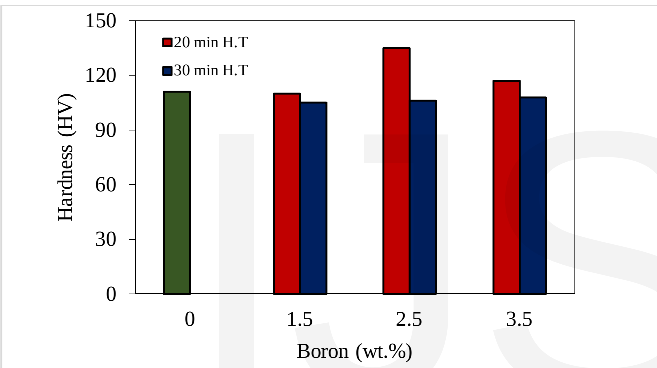

Fig.4 Effect of the boron content and holding time on the hardening of the as-cast samples.

3.2 Effect of boron addition on the heat-treated samples

3.2.1 Hardness measurements

The hardness of the solution heat-treated 7050 Al alloys were measured as the average of five readings for each sample was plotted in Fig.5. It is clearly seen that the sample with 3.5%B and 20 min holding time have the maximum hardness value. While a slight decrease was detected for the same sample with increasing the holding time to 30 min. On the other hand, the hardness revealed slight increase with 1.5 and 2.5%B with increasing the holding time from 20 min to 30 min.

Figure 6 illustrates the effect of aging at 160°C up to 4hrs on the hardening behavior of 7050 Al alloys of different Boron contents and 20min holding time. The addition of 1.5%B increases the hardness up to a maximum value of 166Hv after 2hr aging time. While the addition of 3.5%B exhibit a slight increase in the hardness until it reaches the maximum value of 172Hv after 3hr. The samples contain 1.5% and 3.5%B exhibit a higher hardness as compared to the sample without boron. The sample of 2.5%B shows a remarkable decrease in the hardness as compared to the sample without boron and with the samples of 1.5% and 3.5% B. This may be due to the phase transformation during aging and/or different precipitates formed during aging.

Figure 7 depicts the effect of boron addition at 30 holding time and the aging time on the hardening of 7050 Al alloys aged at 160°C up to 4hr. The results revealed that at an early aging time the hardness slightly decreased for the samples with 1.5 and 2.5%B. While increasing the aging time up to 2hr increase the hardness of the sample with 2.5%B. This sample exhibits the maximum value between all samples about 172Hv. This increase could be attributed to the formation of the hardening phases GPZs and η′. On the other hand, the sample contains 3.5% B exhibit a pronounced increase in hardness up to 2hr aging but with a farther increase up to 4hr, the hardness highly decreased. This decrease in hardness may be due to phase dissolution to form stable η (MgZn2) phase and/or over aging of this sample. From Figs.6 &7 it can be concluded that 1.5%B at 20min holding and 3.5%B at 30min holding time revealed the maximum hardening of the 7050Al alloy. This could be explained by the formation of GPZs and η′phases, which are the main precipitation phases responsible for the hardening of the 7050 aluminum alloy

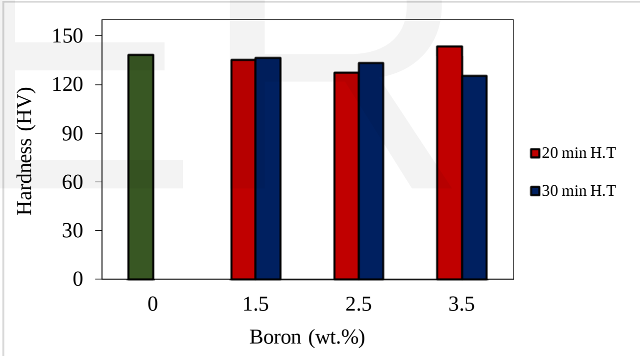

Fig.5 Effect of the Boron content and holding time on the hardening of the solution treated samples.

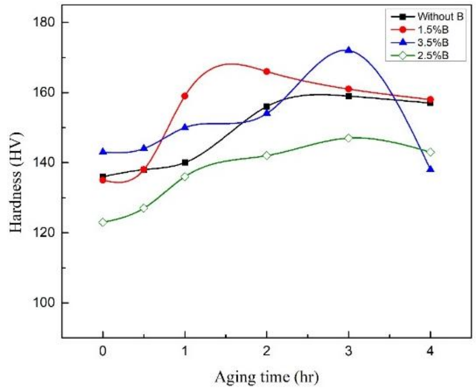

Fig.6 Effect of Boron content and aging time on the hardening of 7050 Al alloy, 20 min holding time and aging temperature 160°C.

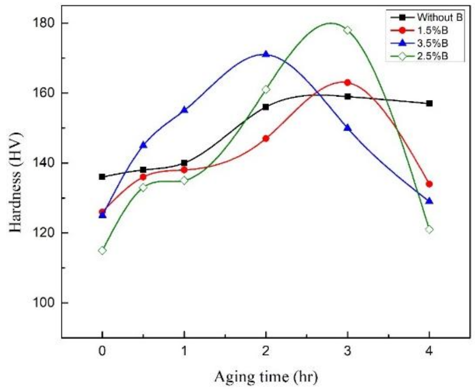

Fig.7 Effect of Boron content and aging time on the hardening of 7050 Al alloy, 30 min holding time and aging temperature 160^{o}C.

3.2.2 Microstructure characterization

To investigate the hardening behavior obtained in Figs.6&7 the microstructure of the 7050 Alloys at the condition that has the maximum hardness shown in Figs.8 &9. The sample without boron after solution treatment before aging, exhibit the maximum hardness compared with the other conditions of the same sample as shown in Fig.7. This due to more precipitates revealed along the grain boundary and inside the grains as shown in Fig.8a. The samples of 1.5% and 2.5%B at 30 min H.T detect the maximum hardness after solution treatment and aging for 3hr as displayed in Fig.7. This also due to the precipitates that formed after aging around the grain boundary and inside the grain as seen in Fig.8-a,d. Moreover, the sample with 3.5%B at 30min H.T revealed the maximum hardness after solution treatment and aging for only 2hr as a result of the precipitates that formed early, Fig.8c. After a 3hr aging of this sample the hardness decrease due to over aging. The sample with 2.5%B exhibits the maximum hardness between all the conditions of all samples because of the finer equiaxed microstructure than the other samples, Fig.8d. Figure 9 reveals the microstructures, which exhibit the maximum hardness value for the other samples with different boron content at holding time 20min. The sample with 1.5%B achieved the maximum hardness at earlier aging time of about 1.5hr and the microstructure revealed precipitates around the grain boundary as shown in Fig.9a. These precipitate could be the hardening responsible η′ phase. While the samples contain 2.5% and 3.5%B exhibit the maximum hardness at 3hr aging and the precipitates formed during aging along the grain boundary and inside the grains, Fig.9b,c. The remarkable decrease in the hardness of the sample with 1.5%B, Fig.6, may be due to the precipitation of the stable η phases that formed with prolonged aging time as depicted in Fig.8a and Fig.9b.

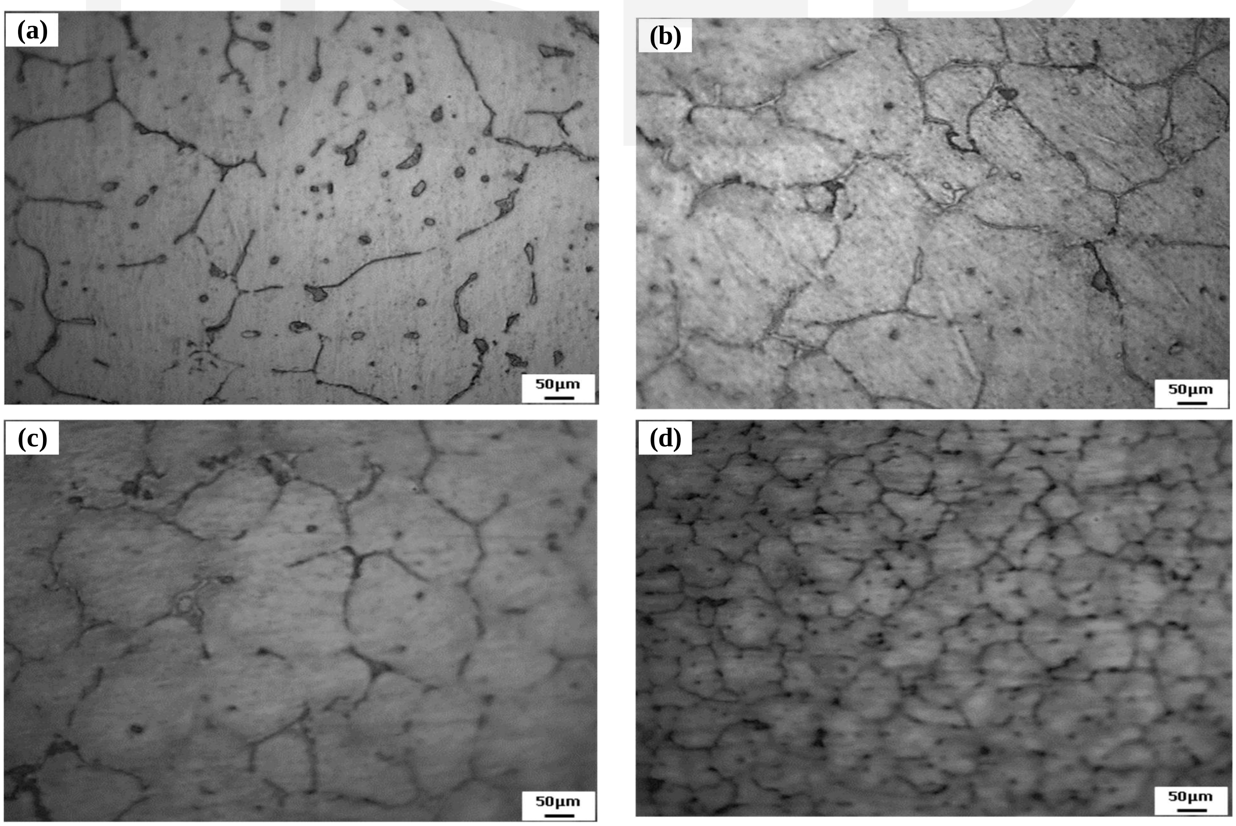

Fig.8 Microstructure of 7050 Al samples after solution treatment at 480^{o}C and aging at 160^{o}C
(a) without B, 3hr aging (b) 1.5%B- 30 H.T, 3hr aging (c) 3.5%B-30 H.T, 2hr aging and (d) 2.5%B-30 H.T, 3hr aging.

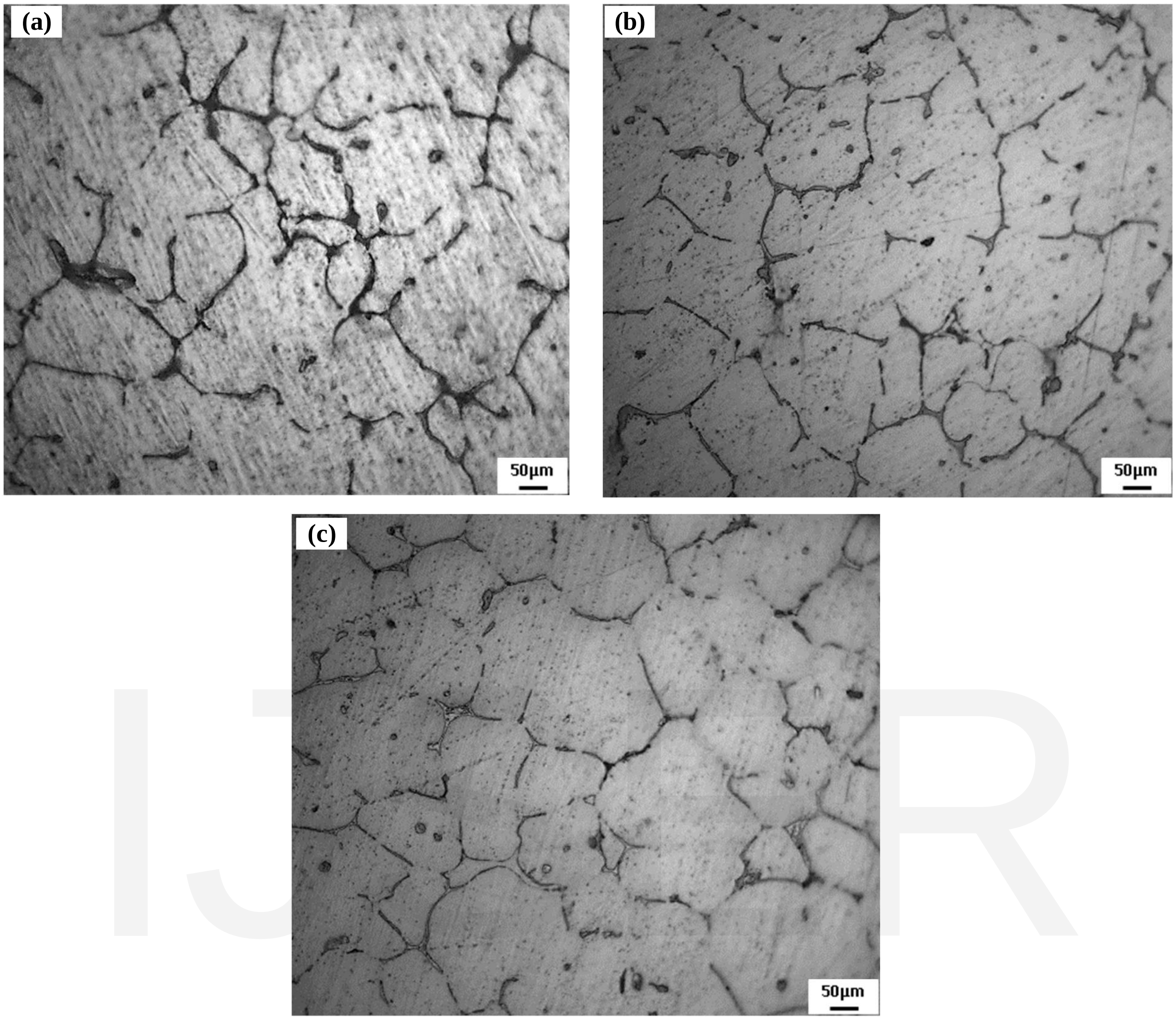

Fig.9 Microstructure of 7050 Al samples after solution treatment at 480^{o}C and aging at 160^{o}C
(a) 1.5%B- 20 H.T, 2hr aging (c) 2.5%B-20 H.T, 3hr aging and (d) 3.5%B-20 H.T, 3hr aging.

3.2.3 Impact test

The impact test was performed for all samples after solution treatment and the results were summarized in Fig.10. Generally, all the absorbed energy increased with increasing Boron content reaches a maximum then decreased with farther boron increase. The holding time of boron before pouring shows a remarkable effect on the impact energy. The sample with 2.5% boron has two contradict values of the absorbed energy according to the holding time as shown in Fig.10 point 1 and 2. The absorbed energy for this sample reaches the maximum value at 30min holding time and this result is in agreement with the coarse microstructure obtained as compared to the other samples at the same holding time. While the same sample at 20 holding time has the minimum absorbed energy. This may be due to the microstructure obtained or the size and the shape of the precipitates formed in this microstructure.

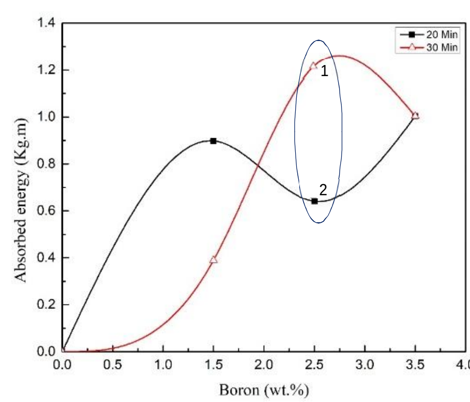

Fig.10 Effect of boron content and holding time on the absorbed energy of 7050 Al alloy

3.2.4 Tensile test

The tensile test was measured for all samples after solution treatment and the results of the ultimate tensile stress (UTS) for the samples without and with boron content at 20 and 30min holding time are plotted in Fig.11. The UTS without boron addition is generally low, while the addition of boron content at 20 min holding time decrease the UTS. On the other hand, the UTS increased to a maximum of about 250MPa for the sample of 1.5%B at 30min holding but with farther boron increase at the same holding time, the UTS decreased. This result is in agreement with the absorbed energy obtained and the macroscopic observation of the used samples.

Thus, it can be concluded that the addition of boron as a grain refining for 7050 Al alloy reveals a pronounced effect on the microstructure, hardening, and properties of the alloy. It is recommended for farther understanding for these results to investigate the nature of the precipitated phases during aging. Moreover, the impact and tensile tests should be measured for the samples after aging to get a clear explanation for the obtained results.

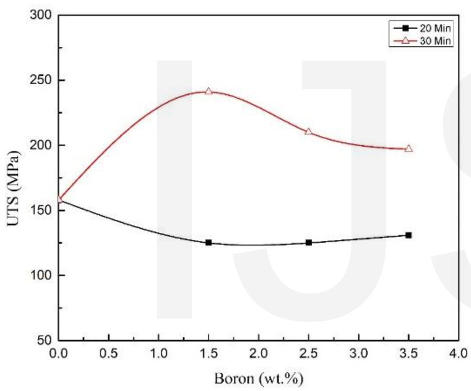

Fig.11 Effect of boron content on the ultimate tensile stress (UTS) of 7050 Al alloy solution treated at 480°C.

4. Conclusions

The effect of the boron content as a grain refiner and the holding time on the mechanical properties and the microstructure of the as-cast and heat treated 7050 Al alloy have been investigated. The main results can be summarized as follows:

- Addition of boron at a different holding time highly affect the grain size structure, changing the dendritic structure into the equiaxed structure for the as-cast alloys.
- The more fine structure obtained with 3.5% B at 20 and 30-minute holding time before pouring as compared with 1.5 and 2.5% B at the same holding times.
- The maximum hardness obtained for the samples of 1.5% Boron at 30min H.T and 3.5% Boron at 30min H.T after solution treatment due to fine structure and the precipitates.
- The maximum hardness of 135 HV obtained for the sample with 2.5% B at 20 min H.T after aging for 3hr, while the structure is not that fine to obtain this value, this could be explained due to the precipitated phases.
- After heat treatment (S.T & Aging) the precipitates formed along the grain boundary and inside the grains in all samples.
- The sample with 1.5% boron at 30min holding time revealed the highest UTS but with increasing the boron content at the same holding time the UTS decreased.

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