Effect of Molybdenum Addition to Aluminum Grain Refined by Titanium plus Boron on Its Metallurgical Aspects and Mechanical Characteristics

Adnan I. O. Zaid

Abstract— Aluminum, Aluminum, alloys and its microalloys have become during, the last century one of the most important constructionalmaterials despite their complex and expensive extraction due to their attractive and required physical and mechanical properties. However, against these beneficial properties they have the disadvantage of solidifying in columnar structure which tends to reduce their mechanicalstrength and deteriorate their surface quality. Hence, it is becoming a necessity to grain refine their microstructures to overcome thesediscrepancies. It is therefore anticipated that addition of some rare earth refiner elements is worthwhile investigating. In this paper, theeffect of addition of Ti-B and Mo to the aluminum melt prior to solidification at a weight percentages which corresponds to the peretecticlimit on their phase diagrams on its microstructure, mechanical characteristics, and Vickers microhardness in the as cast condition isinvestigated. It was found that addition of any of them either alone or together caused refining of its structure by pronounced decrease ofits grain size. Moreover, addition of Mo in the presence of Ti- B caused further decrease in the grain size. Hence it might be concluded that addition of Ti- B or Mo to aluminum prior to solidification led to a transition from predominantly columnar large grain structure to an equiaxed fine grain size one.

Index Terms— Effect, Molybdenum addition, Aluminum refined, Titanium, plus boron, Grain size, Columnar structure, Equiaxed, Microstructure, Mechanical characteristics, Hardness.

1 Introduction

ALUMINUM and its alloys are widely used in the aircraft and automobile industries for manufacturing several original and spare parts due to their attractive and useful properties; such as their high strength- to- weight ratio, their high thermal and electrical conductivities in addition to their good resistance to corrosion. They are used in manufacturing thin foils, .beverages cans vessels and many aircraft and automobile parts.

However. Against these beneficial properties they have the disadvantage of solidifying in columnar structure of large grain size. This tends to reduce their mechanical strength and deteriorate their surface quality. Therefore, to avoid this deficiency they are normally alloyed with Cu, Mn or Mg or microalloyed with other rare earth elements such as Ti, Ti- B, Mo, V,…etc. Hence, grain refinement is an important opportunity to overcome this discrepancy and improve mechanical properties and the surface quality. Furthermore, aluminum and its alloys have high affinity to oxygen which makes them very difficult to weld in the open atmosphere due to the formation of oxide layer on the surface.

1.1 Alloying Aluminum with Metal Elements

Aluminum has a high chemical affinity to oxygen and silicon. It is therefore does not exist in the Earth`s crust as pure metal and needs to be extracted from its oxides, Al2O3, which such as thin foils, beverage cans, vessels or aircraft components is a very stable chemical compound. Hence, aluminum can not be extracted easily by a common chemical oxidation process due to the presence of some impurities of elements which are lighter than Al. Hence it needs fused-salt electrolysis to extract Al from the oxides [1]. This process, however, needs plenty of energy, which explains the high production costs for primary aluminum compared to other metals, [2].

The properties of pure aluminum can be improved significantly with alloying elements where the most important ones are copper, manganese, magnesium, silicon and zinc. Aluminum alloys are generally classified into two groups one is the cast alloys which are Al-Si alloys with Si contents between 5 and more than 20 wt.-% providing a good castability and the second is the wrought alloys, which are in contrast to cast alloys, they have a high deformability and strength and they are used for rolling and extrusion products such as films, plates or profiles, [3]. Alloying Aluminum with Metal elements is beyond the scope of this paper and only microalloying will be dealt with.

1.2 Microalloying Aluminum with Rare Earth Elements, Grain Refinement, [4- 8]

As early in 1949, Cibula [4, 5] showed that the presence of titanium, particularly in combination with carbon or boron, produces a good refining effect in aluminum. Since then , it became an industrial practice to add titanium , either alone or with boron , to grain refine aluminum and its alloy , Originally , salt mixture such as K2 TiF6 with KBF4 or borax were added for the Al melt for this purpose. However, this method gives

• *Adnan I. O. Zaid is currently a professor in mechanical engineering in Applied Science University, Jordan. E-mail: adnan_kilani@yaahoo.com*

variable recoveries of titanium and boron in addition to producing troublesome slag and fumes. Furthermore, the use of salts requires a high and costly addition rate to achieve a satisfactory grain refinement and unwelcome buildup of Ti and B in recycled scrap could occur. For these reasons the use of salts was stopped and superseded by the use of master alloys. Since 1949, when Cibula reported that the presence of the titanium particularly in combination with carbon or boron, produces a good grain refining effect in aluminum which turn enhances the mechanical behavior and surface finish, the aluminum cast industry has increasingly been adding titanium alone or with boron; furthermore, continuous attempts and research were carried out to find out the optimum addition level of Ti and the optimum ratio of Ti-B in the ternary Al-Ti-B master alloy where Several binary and ternary alloys have been developed for this purpose.

Al-Ti binary and Al-Ti-B ternary master alloys of different composition have been developed for the grain refining of aluminum and its alloys. A typical binary Al-Ti master alloy would contain 6-10% wt. Ti with the titanium content present almost entirely in the form of crystalline intermediate compound $TiAl_3$. The ternary Al-Ti-B master alloy in common use contain 5% Ti and 1% B, wt. and has two crystalline intermetallic compounds, namely: small crystallites of titanium diboride and larger crystals of $TiAl_3$ [6]. Mass for mass , the ternary AL-5%Ti – 1%B master alloy is usually about five to six times more efficient than a binary Al-mas , the ternary Al-5%Ti-1%B master alloy is usually about five to six times more efficient than the binary Al-6%Ti master alloy [6-8].

2 Materials, Equipment and Experimental Procedures

2.1 Materials

The following materials were used throughout this thesis.

High purity molybdenum of 99.98% purity titanium and aluminum powders of 99 99% purity were used in manufacturing Al –Ti and Al-Mo master alloys which were later used for manufacturing the different microalloys. Graphite crucibles were used for melting and graphite rods were used for agitation.

TABLE 1
CHEMICAL COMPOSITION (WT. %) OFCOMMERCIALLY PURE ALUMINUM

Element	Wt %
Al	Rem
Na	0.005
Mn	0.001
Zn	0.005
V	0.008
Ti	0.004
Mg	0.004
Cu	0.005
Si	0.05
Fe	0.09

2.2 Equipment and Experimental Procedures

The experimental procedure stated by preparing the base metal, Al, and the different binary and ternary master alloys as follows:

2.2.1 Preparation of the Al Base Metal

The commercially pure bundles of the Al wires, supplied by the Jordanian Electricity Authority, were pickled in HNO33to remove the oxide layer and any other contaminant, then melted in a graphite crucible inside an electric furnace at 800oC and then poured to solidify in hollow rectangular brass rods of 10 mm inside width and 55 mm external width, Fig.1. Finally, the rods were rolled into sheets of 3 mm thickness, 10 mm width and 240 mm length.

Fig. 1. Photograph showing the thick rectangular cross sectional brass die.

2.2.2 Preparation of the Binary Master Alloys, Al-3% Mo and Al-5% Ti

The Al–3% Mo and Al-5% Ti binary master alloys were prepared by adding the calculated amount of Mo to the predetermined amount of molten aluminum in the graphite crucible at 850oC for Al–Mo binary master alloy, stirred by the graphite rod for one minute and brought back to the furnace for 20 minutes, brought out and stirred again for one minute and then poured to solidify in the thick brass rods .Finally the rods were rolled into sheets of 3 mm thickness,10 mm width and 240 mm length.

The two prepared master alloys were used for preparing the Al- Ti and Al- Ti- Mo mjcroalloy.

Fig. 2. Photograph shows the ternary Al- Ti- Mo after solidification inside the brass die.

3 Results and Discussion

3.1 Effect of Mo addition to Al and Al grain refined by Ti and Ti-B on their grain size

Fig.6 shows the general microstructure of commercially pure Al and its alloys. The grain Size of Al and its alloys Al- 0.1 % Mo, Al-Ti- B andAl-Ti- B- Mo before welding as solidified in air. A slow cooling process. It can be seen from Fig. 6 (a) that Al solidified in columnar structure of large grain size, 175 micron. Also it can be seen from this figure that addition of Mo or Ti-B to Al resulted in refining its structure to equiaxed one of smaller grain size where a decrease of 45.32 %, 47.48 % by addition of Mo and Ti-B respectively, whereas 66.91 % reduction was achieved when both were added together. The flow stress at 10 % strain was found as 70 MPa [8].

Table3: and Fig. 4 show the effect of addition of Ti, Ti-B to Al. It can be seen from this figure that addition of Ti resulted in poisoning its structure as it resulted in increasing the grain size by 27.27 % while the addition of Ti-B resulted in refining its structure by decreasing its grain size by 10 %. Furthermore it can be seen from this figure that addition of Mo to Al grain refined by Ti or Ti-B resulted in refining their structure by decreasing the grain size by 18.18%, and 4.55 % respectively. The poisoning effect of Ti addition is due to the interphase of aluminide whereas the refining effect of the Ti B is due to the boride interphase in the main matrix although boron itself is not a refiner when added alone.

TABLE 3
The Grain size of Al and its alloys before the welding process

Grain Size (Micro)	Material
22	Al
20	Al-Ti-B
21	Al-Ti-B-Mo

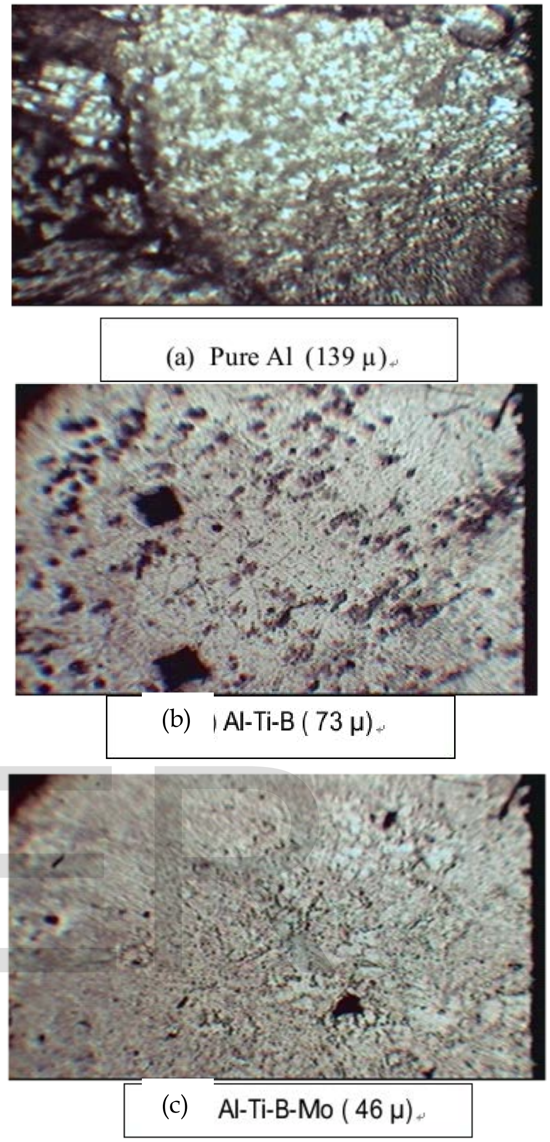

Fig. 3. Photomicrographs showing the original microstructure of commercially pure Al and its alloys: Al- 0.1 % Mo, Al- Ti- B and Al-Ti-B-Mo as cast condition after solidification..

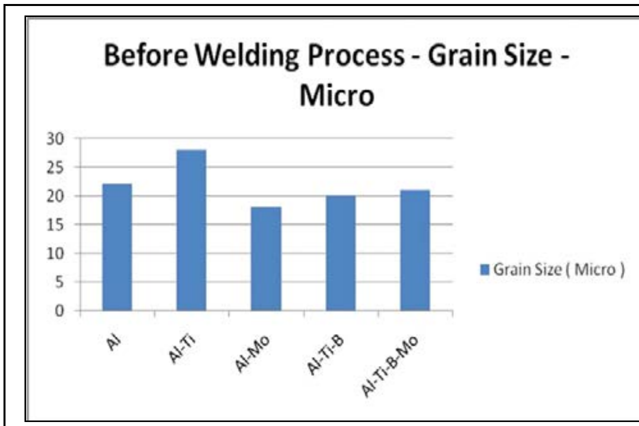

Fig. 4. A histogram showing the grain size of Al and its microalloys after rolling.

ISSN 2229-5518

The grain size of Al, Al- Ti- B and Al- Ti- B- Mo are explicitly shown in Figs 5 (a), (b), and (c) respectively.

Fig. 5 (a). Photomicrograph of the original microstructure of Al specimen, X 120.

Fig. 5 (b). Photomicrograph of the original microstructure of Al-Ti-B specimen, X 120

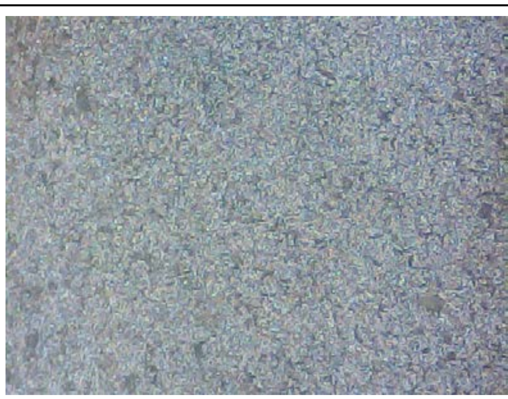

Fig. 5 (c). Photomicrograph of the original microstructure of Al-Ti-B-Mo specimen, X 120

The photomicrographs of Figs. 8(a) to Figs. 8(e) inclusive show the effect of addition of Ti , Ti-B ,Mo , Ti-B-Mo to Al on its weldability both in the HAZ and base region. The metallurgical examination revealed that addition of Ti or Ti-B

3.2 Effect of Ti-B and Mo addition to Al on its mechanical behavior and characteristics

Table 4 and Figs. 6 to 8 inclusive show the effect of Ti-B and Mo addition to Aluminum on its mechanical behavior. It can be seen from these figures that the addition resulted in appreciable enhancement of its mechanical behavior represented by increase of its flow stress at 10 % true strain by 67.9 %and 102.3 % respectively. This is attributed to the grain refinement of their structures as explicitly illustrated and discussed in the photomicrographs of Figs. 5 (a), (b) and (c), for Al-Ti-B and Al-Ti-B-Mo respectively. These photomicrographs reflect that the addition of any of them resulted in changing the general microstructure of cast aluminum from columnar structure with large grain size into equiaxed structure with fine grain size.

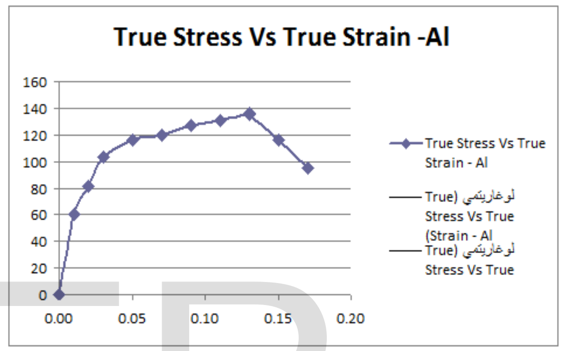

Fig. 6 True Stress Vs True Strain diagram for Al in Tension

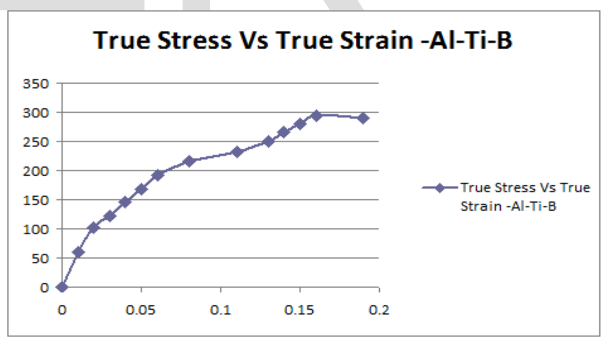

Fig. 7. True Stress Vs True Strain diagram for Al-Ti-B

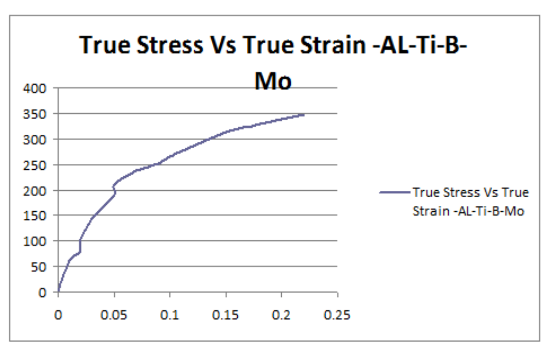

Fig. 8. True Stress Vs True Strain diagram for Al-Ti-B-Mo

Table 4 gives summary of the effect of the addition of Ti-B and Mo to Al on its mechanical characteristics in the last column to allow direct comparison. The general equation of the average mechanical behavior illustrates that the strength factor of Al has increased from 250 MPa in the cast condition to 400 and 680 MPa i.e. by the addition of Mo to Al refined by Ti or Ti- B respectively, Moreover, the strain hardening index has increased appreciably, more than doubled, by the addition Mo to Al refined by Ti- B. This causes increase in its strain at plastic instability which in turn will increase its formability in general and in rod, deep drawing and redrawing processes in particular which are the most widely used forming processes in the automobile and aircraft industries. This will widen their usage and makes them more cost effective.

TABLE 4
MECHANICAL CHARACTERISTICS OF COMMERCIALLY PURE AL AND ITS ALLOYS

Material	Flow Stress at 10 % strain-Mpa	U.T.S	Max Elongation %	Max Reduction %	General (n) Equation
Al	131	140	19	16	$\sigma_T = 250\varepsilon_T^{0.2}$
Al-Ti-B	233	300	21	17.8	$\sigma_T = 650\varepsilon_T^{0.45}$
Al-Ti-B-Mo	265	350	24	20	$\sigma_T = 680\varepsilon_T^{0.42}$

3.3 Effect of Ti-B and Mo addition to Al on its Vickers microhardness

Vickers microhardness measurements were taken over the prepared specimens for the metallurgical examination. Ten measurements were taken on each specimen covering the surface of the specimen and the arithmetic mean was taken, after cancelling the values which varies more than 3 % from the mean, as the average of the Vickers microhardness. The values of these measurements are presented in the histogram of Fig.9. It can be seen from this figure that addition of Ti or Mo to Al resulted in decrease of its microhardness by 25 % and 10 % respectively. However addition of Ti-B resulted in increasing its microhardness by 13.33 %. Furthermore addition of Mo to Al-Ti-B brought back its microhardness to the same value of Al-Mo microalloy.This is attributed to the decrease in the grain size and the interphases within the main matrix.

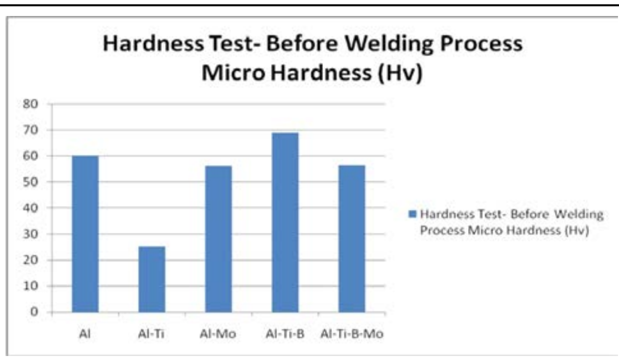

Fig. 9. Micro Hardness (Hv) for pure Al and its microalloys

CONCLUSION

From the results of the research work in this paper, the following points are concluded:

i). Addition of Ti-B or Mo to to commercially pure aluminum resulted in modification of its microstructure from large grainscolumnar structures into equiaxed fine grains structures beingmore efficient in case of Ti-B addition. Furthermore, addition of Ti-B and Mo together and the rolling process resulted infurther refinement of the casted ones.

ii). The addition of Ti-B to Al has resulted in increase of thflow stress at 10 % strain and the UTS by 114.3 % and 77.86 %respectively.

iii). Similarly, the addition of Ti- B to Al has resulted in increase of its Vickers microhardness.

iv). In summary, grain refinement of Al and Al grain refined byTi- B and the addition of Mo to Al grain refined by Ti or Ti-B to the melt before solidification is a very powerfultechnique which overcomes the discrepancies resulting from its solidification in columnar structure of large grain size.

ACKNOWLEDGEMENT

The author would like to acknowledge Dr. Ahmad Omar Mostafa for formatting the paper.

REFERENCES

[1] McCawley and L.H. Baumgardner: "Mineral Facts and Problems", in Aluminum, 1985 edition, United States Department of the Interior, Washington.

[2] D. Altenpohl, (1970), Aluminum von innen betrachtet, 2nd edition (in German), Aluminum-Verlag, Düsseldorf.

[3] E. Roos and K. Maile, (2002), Werkstoffkunde für Ingenieure, 1st edition (in German), Springer, Berlin.

[4] Cibula. A, (1949-1950), Journal Institute of Metals, V.76, pp.321-360.

[5] Cibula. A, (1950-1951), Journal Institute of Metals, V.80, pp.1-15.

[6] Abdel Hamid, A. A., (1985). On the mechanism of the grain refinement of aluminum by small addition of Ti and B, The Second Arab Aluminum Conference ARBAL,8in 5, Egypt, Oct.

[7] Jones, G.P. and Pearson, J. (1976), Factors Affecting Grain Refinement of Aluminum Using Titanium and Boron Additives Metallurgical Transactions, pp.223-234.

[8] Zaid A'I.O, (2001), Grain refinement of aluminum and its alloys, Proc. International Symposium on Advanced Materials, isam 2001, Islamabad, Pakistan.