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Effect of Molybdenum Addition to Aluminum Grain Refined by Titanium plus Boron on its Mechanical Characteristics, Ductility and Formability

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Abstract— Aluminum, Aluminum, alloys and its microalloys are the second used materials in engineering and industrial application particularly in aircraft and automobile industries due to their required properties, e.g. high strength- to- weight ratio, electrical and thermal conductivities in addition to their good resistance to corrosion. However, beside these attractive and useful properties they have the discrepancy of solidifying in large grain columnar structure which is adversely affect their mechanical strength and surface quality. It is therefore, very essential to refine their structure to avoid these defects. The available literature reveals that they are normally refined by Ti or Ti-B master alloys which are commercially available. In this paper the effect of Mo addition to commercially pure aluminum refined by Ti-B on its mechanical characteristics and ductility Is investigated. It was found that the obtained results are presented and discussed.

Index Terms— Effect, Molybdenum addition, Aluminum refined, Titanium, plus boron, Mechanical characteristics, Ductility, Formability.

1 Introduction

ALUMINUM and most of its alloys solidify with a coarse columnar structure in the absence of grain refiners, whereas fine and equaxed grain structure is obtained by the addition of small amounts of Ti or Ti - B into the melt before casting, [1] . When Ti is added alone, its presence in the melt must exceed the peritictic composition of about 0.15% by weight, to obtain a satisfactory grain refining effect. However in the presence of boron, even in ppm order, an important refinement is obtained at Ti contents as low as 0.005 %, [2, 3]. Experience, based on experimental results, has shown that optimum grain refining properties are achieved using Al-Ti-B master alloys with Ti to B ratio about 5. [4, 5, 6, 7, 8]. It has been reported that boron has the greatest enhancing effect on the grain refining efficiency of Ti in the aluminum casting although boron itself is not a grain refiner when added alone. The ternary Al-Ti-B master alloy in common use contains 5% Ti and 1% B, wt. and has two crystalline intermetallic compounds, namely: small crystallites of titanium debride and larger crystals of $TiAl3$ (2). 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-Ti master alloy. (2, 3).

1.1 Mechanism of Grain Refinement

The increasing and increasingly efficient use of additions of Al-Ti-B master alloys has been justified from the technological and scientific point of view, although the mechanism of grain refining of Al and its alloys by these mater alloys is still a controversial matter and further work needs to be carried out before it is determined It appears that more than one mechanism is responsible of the grain refinement, depending on the master alloy used , the cast alloy and the prevailing process conditions or parameters . Several suggestions have been made to explain the mechanism, [6, 7, 8, 9]. It was reported that the grain refinement of aluminum is due to the nucleation of Al by the aluminide particles, or by boride particles, [1, 6] or by TiB2 particles coated with TiAl3 "duplex particles", [11, 16, 17]. Abdel-Hamid [8] has discussed the mechanism and showed that a high local Ti-concentration exists in the vicinity of TiB2 particles making high efficient nuclei for Al grain. Recently, the local Ti-enrichment associated with TiB2 particles has also been suggested by others [13, 33].

1.2 1.2. Parameters Affecting Grain Refiners Efficiency, [3, 4]

a) The composition, (Ti concentration and Ti to B ratio) in the grain refining master alloy and its microstructure (size and morphology of TiAl3 and TiB2 particles).

b) The rate of addition of the master alloy.

c) The melt Temperature and holding time (contact time) before casting.

d) The purity or composition of the aluminum cast.

e) The level of impurity such as Fe, Si or the presence of some alloying elements which can enhance the grain refining efficiency e.g. V, Mo, Nb, [17, 18, 21] or poison it e.g. Mn, Zr, Ta and Cr [19, 20, 22, 30, 31]. Although, the effect of the different microalloying by different refractory metals on aluminum and its alloys has been concern in the literature for more than five decades most of the work is directed towards the effect on the grain refinement of these elements and little attention has been given to their effect on the mechanical behavior machinability and fatigue life and strength of aluminum. It was only recently when Zaid and Abdel-Hamid (23-24) reported the effect of microalloying with V or Zr on mechanical behavior and machinability and more recently the effect of

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Mo and Ta was reported in references (25 , 36) . The effect of these elements on the fatigue life and strength was investigated and reported in Refs. [37, 38]. include: Purity: high or commercial chemical composition: wt. % of each element , impurities and residuals , recycling % method of production :cast or formed.

ii). Parameters Related to the grain refiner: Chemical composition : Ti and B levels , Ti-B ratio , residuals or impurities , Manufacturing process , Form : salts , foil , sheet , rod or ingot, grain size, uniformity of distribution of Grain The grain refinement efficiency is affected by many factors these are summarized in Table 1: under three heading namely :parameter related to Al alloy melt , parameters related to the grain refiner itself and finally parameter related to the procedure followed in carrying out the grain refinement process . the effectiveness of the grain refinement depends on the purity of Al melt . The presence of small amounts of impurities or alloying elements can strongly affect the grain refining efficiency.

The following parameters affect the performance of grain refinement:

i). Parameters Related to the Al and Al –Alloy Melt:

These refining particles and the addition levels. . iii). Parameters Related to the process of grain refinement: methods of addition: one set or more, furnace atmosphere, the addition temperature, holding or contact time (fading), stirring time, pouring temperature and rate of cooling: inside the furnace or in air. For example it was found that the grain refining of pure Al by Ti was increased by 100% when the Al purity was decreased from 99.999% to 99.99% (42) . moreover , an efficient grain refinement of the 99.99% Al by Ti and B can be produced only in the presence of excess Ti or other solutes such as Si and Fe (29,43) it is also reported that the presence of some alloying elements particularly Si, Fe, Mg and Zn improves the grain refining efficiency of the Al -5 % Ti-1% B master alloy and this improvement increases with increasing amount of alloying constituents , (2,43) .Some studies has been carried out on the enhancing effect of one or more elements on the grain refinement of Al by Ti and B , aiming to develop a new ternary grain refining alloy replacing the conventional Al-5%Ti-1%B alloy (39).

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 PROCEDURE

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.

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 mechanical behavior and characteristics

Figures 3 to 5 inclusive and Table 2 show the effect of Mo addition to Aluminum and Aluminum grain refined by Ti and Ti-B on their mechanical behavior represented by their true stress—true strain curves. It can be seen from these figures that the addition resulted in appreciable enhancement of their mechanical behavior represented by increase of their flow stresses 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. 8 (a), (b), (c), (d) and (e), for Al, Al- Ti, Al-TI-Mo, 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, 139 micron into equiaxed structure with fine grain size.

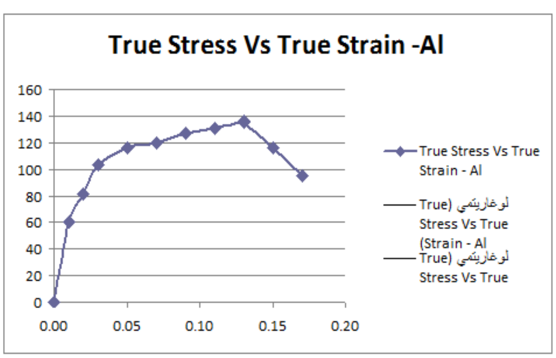
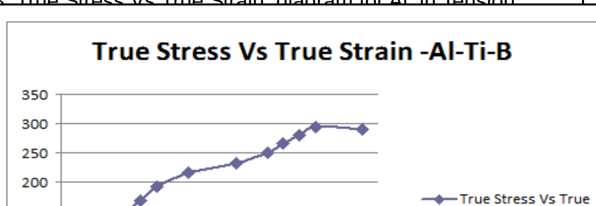


Fig. 3. True Stress Vs True Strain diagram for Al in Tension



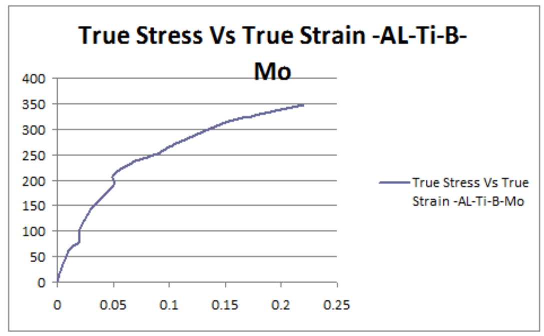


Fig. 5. True Stress Vs True Strain diagram for Al-Ti-B-Mo

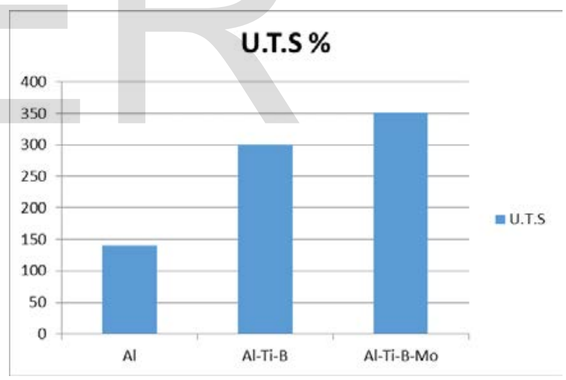


Fig. 6. The Ultimate tensile strength , UTS, of Al , Al-Ti-B and Al-Ti-B-Mo alloys

Table 2 gives summary of the effect of the addition of Mo to Al grain refined by Ti and Ti- B on its mechanical characteristics as obtained from the above figures 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, Also addition of Ti- B has resulted in pronounced increase in the work hardening index by 125%; this illustrates the increase in its formability which allows more plastic deformation before plastic instability is reached especially in metal forming processes which requires high plastic true strains before the plastic instability is attained e.g. rod drawing, deep drawing, redrawing and heavy plastic deformation processes. This will reduce the number of stages, preforms, which will reduce the number of the required die set; which in turn will cause decrease in the production cost making the material more cost effective.

3.2 Effect of Mo Addition to Al Grain Refined by Ti- B on its Ductility

TABLE 2
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	$\sigma_T = 680\varepsilon_T^{0.42}$

The effect of Mo addition to Al on its ductility is investigated through the results of the standard tensile tests which was carried out in accordance of ASTM Standards. Figs.6 and 7 show the effect on the maximum elongation percentage and the maximum reduction in area percentage respectively.

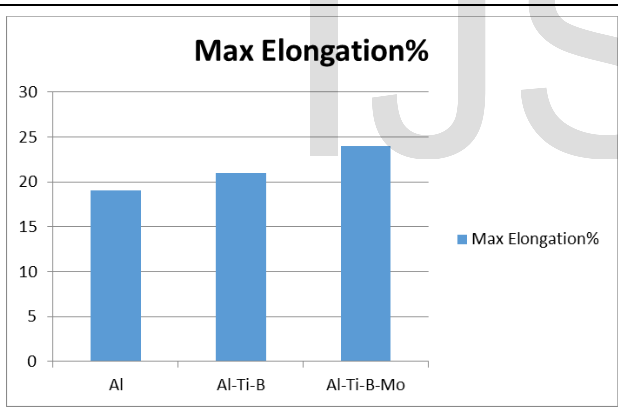
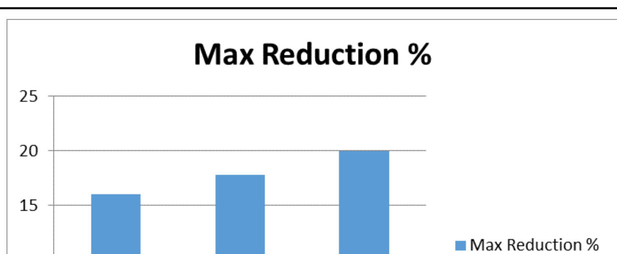


Fig. 7 Maximum Elongation % of Al, Al-Ti- B and Al-Ti- B- Mo alloys

It can be seen from Table 2 and Fig. 7 that addition of Ti- B resulted in increase of 10.53 % in its maximum elongation percentage and 11.25 % in its maximum reduction in area. Furthermore, addition of Mo to Al refined by Ti- B resulted in 26. 53 % and 25 % in the maximum elongation percentage and 25 % in the maximum reduction in cross sectional area respectively.



4 CONCLUSIONS

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

i). Addition of Ti- B to commercially pure aluminum resulted in enhancement of its mechanical behavior represented by increase in its flow stress at 10 % strain and the UTS by 114.3 % and 77.86 % respectively. Similarly, it resulted in improvement of its other mechanical characteristics: strength factor and work hardening index.

ii). Addition of Mo to Al grain refined by Ti- B to Al resulted in further improvement of its flow stress, UTS, and strength coefficient but reduced its work hardening index,

iii). Addition of Ti- B to Al resulted in improvement in its ductility where an increase of 10.53 % and 11.25 % in the maximum elongation and maximum reduction in cross sectional area percentages respectively. Furthermore, addition of Mo to Al grain refined by Ti- B to Al resulted in further enhancement of its ductility.

iv). Addition of Ti- B to Al resulted in pronounced improvement in its formability represented by the great increase in the work hardening index by 125 % which allows more plastic deformation before plastic instability is reached.

In summary, the addition of Ti- B to Al melt before solidification is a very powerful technique which overcomes the discrepancies resulting from its solidification which caused pronounced enhancement in its mechanical characteristics and its ductility and great improvement in its formability. Addition of Mo to Al grain refined by Ti- B to Al resulted in further improvement of its formability. This will make it more cost effecyive.

REFERENCES

[1] Cibula. . Cibula. A, (1949-1950), Journal Institute of Metals, V.76, pp.321-360.
[2] Cibula. A, (1950-1951), Journal Institute of Metals, V.80, pp.1-15
[3] Jones, G234..P. and Pearson, J. (1976), Factors Affecting Grain Refinement of Aluminum Using Titanium and Boron Additives Metallurgical Transactions, pp.223.
[4] Zaid, A.I.O., 2001 "Review of the Grain Refinement of Aluminum and its Alloys" Proc. of the InternationalSymposium on Advanced Materials, ISAM,

Islamabad, Pakistan, 2001.

[5] Abdel Hamid A.A. and Zaid, A.I.O. (2000), ―Poisoning of Grain Refinement of Some Aluminum Alloys‖, Seventh, Cairo Intern. Conference, Current Advances in Mechanical Design and Production, Cairo, Feb 2000, pp.331-338.

[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 ,85, Egypt, Oct.

[7] Pearson, J. and Birch, M. E. J. (1979), The Effect of the titanium Boron Concentrations on Aluminum Grain Refining Alloy. Journal of Metals, V. 31, No.11, pp.27-31.

[8] Zaid A. I. O, Al-Qawabah S.M.A., (2011), Effect of zirconium addition on the grain size and mechanical behavior of aluminum grain refined by titanium plus boron (Ti+B) in the as cast and extruded conditions, Proceedings of the 12th International Symposium on Advanced Materials (ISAM-2011), Islamabad, Pakistan.

[9] Wang W. D., Ma Y.C., Chen B., Gao M., Liu K., Li Y.Y., (2010), Effects of boron addition on grain refinement in TiAl-based alloys, J. Mater. Sci. Technol. Vol. 26, PP. 639–647.

[10] Hecht U., Witusiewicz V., Drevermann A., Zollinger J.,(2008), Grain refinement by low boron additions in niobium-rich TiAl-based alloys, Intermetallics. Vol. 16, PP.969–978.

[11] Hyman M.E., McCullough c., Valencia J.J., Levi C.G., Mehrabian R., (1989), Microstructure evolution in TiAl alloys with B additions: conventional solidification, Metall. Trans A. Vol. 20, PP. 1847–1859.

[12] Zaid. A. I. O, (2006), Grain Refinement of Zn- Al Alloys, Proceedings of the Second International Conference on the Frontier of Advanced Engineering Materials, FAEM- 2006, Lahore, Pakistan

[13] Zaid, A. I. O. and Hussein, M.I.J., (2005), Effect of Zirconium Addition on the Mechanical Behavior and Wear Resistance of Zamak5 Alloy. Proceedings of the 9*tth* International Symposium on Advanced Materials, ISAM, 2005, Islamabad, Pakistan.

[14] Zaid. A.I.O. and AL-Dous, Z. M.A., (2006), ―Effect of Zirconium Addition on the Ductility and Toughness by Titanium, Proceeding of the Second International Conference on the Frontiers of Advanced Engineering Materials, 2006, Lahore, Pakistan.

[15] Zaid. A. I. O. and Hussein, M.I.J., (2006), Effect of Zirconium Addition on the Mechanical Behavior and Wear Resistance of Zamak5 Alloy Grain Refined By Titanium. Proceedings of the 12*tth* International Conference on Machine Design and Production, 2006, Kusadasi-Turkey.

[16] Zaid. A. I. O, Al-Qawabah S. M. A, Nazzal, M. A, (2011), Effect of Titanium or Titanium-Boron Addition on the Formability of Commercially Pure Aluminium", 21th International Conference on Production Research, 21 ICPR, St

[17] .Zaid. A. I. O, (2001), Grain Refinement of Aluminum and its Alloys, Proceedings of the 7th International Symposium on Advanced Materials, ISAM-2001, Islamabad, Pakistan.

[18] Said R. Gasolco, J. Negrete-Sanchez, G. and Torres-Villosen-or, (2003),Influence of Silver on the Mechanical Properties of Zn-Al Eutectoid Su-per plastic alloy, Materials Characterization, V. 51, pp.63-67.

[19] Assifa, M. M., (2011), Effectiveness of Naphthalene in Grain Refinement of Commercially Pure Aluminum and Zinc Ingot Castings, Engineering & Technology Journal, V-29, Issue 8, pp 1545-1553.

[29] Azad. A. Bichler,and Elsayed, A. (2013), Effect of a Novel Al-SiC Grain Refiner on the Microstructure and Properties of AZ91EMagnesium Alloy, International Journal of Metal casting, V-7, Issue 4, pp 49-60.

[21] Jianchao Han, Shulong Xiao, Jing Tian, Yuyong Chen , Lijuan Xu, Xiaopeng Wang, Yi Jia, Zhaoxin Du, Shouzhen Cao, Grain refinement by trace TiB2 addition in conventional cast Ti-Al-based alloy, Materials Characterization, V.106, pp. 112–122.