Effect of Tantalum Addition to Zinc-Aluminum alloy5, ZA5, on its Metallurgical Aspects and Mechanical Characteristics

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Abstract— the use of Zinc-aluminium alloys in general and Zinc-aluminium 5 alloy have spread in the last three decades in industrial applications, due to their resistances to wear and corrosion. These alloys normally solidify in coarse dendritic structure which affects their surface quality and mechanical behaviour. Therefore, their structure is normally refined by rare earth materials e.g. titanium, titanium+boron or zirconium. In this research the effect of addition of Tantalum to ZA5 at the following percentages: 0.02%, 0.04%, 0.06%, 0.08% and 0.10% on its microstructure, hardness, mechanical behaviour, and fatigue life is investigated. The results of this work revealed, within the experimental range, that the addition of Tantalum as grain refiner at all rates resulted in changing the coarse dendritic structure of ZA5 into fine nodular one which resulted in enhancement of its hardness and flow stress. It was also found that addition of 0.04% Tantalum to ZA5 resulted in enhancement of its flow stress, and the fatigue life at a stress level of 160 MPa. However, addition of Ta at a rate percentage higher than 0.04% and at stress level exceeding 160 MPa resulted in deterioration of its fatigue life.

Index Terms— Effect of tantalum addition, Zinc-aluminium 5 alloy, Metallurgical aspects, Mechanical behavior and characteristics, Vickers hardness, Mechanical behavior equation of state.

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1 INTRODUCTION

THE use of Zinc-Aluminium alloys in general and Zinc-Aluminium 5 (ZA5) alloy have been largely used in industrial and engineering applications in the last two decades. They are mainly used in automotive and aircraft industries, due to their relatively high strength-to-weight ratio and their good resistances to wear and corrosion. Recently, these alloys are reported to replace brass in bushes and bearings.

Zinc-Aluminium 5 alloy, which will be referred to later as ZA5, is mainly used for die casting due to its low melting point which ranges from 375-487oC beside the previously mentioned reasons [1]. This alloy is produced by alloying Zinc with aluminium and other elements e.g. iron, lead, cadmium and tin. The main function of these alloying elements is to produce strengthening and improve formability. However, the maximum solubility of these elements is limited being 0.100%, 0.005%, 0.003% and 0.004% respectively [2]. Concentrations larger than these values will have adverse effect on the corrosion resistance and inter-granular attack which occur in many environments causing the die casting to be extremely weak [1].

As zinc-aluminium alloys in general and ZA5 in particular are used for die casting and normally solidify in coarse dendritic structure which tends to reduce their mechanical strength and surface quality, researchers started to modify their structures by adding some alloying elements of rare earth materials on the micron level e.g. Ti, Ti+B, Zr to their melt before solidification [3-9]. The main research work was directed towards modification of the structure by grain refining. Recently, research work was carried out by investigating the effect of addition of some rare earth materials on the mechanical strength, wear resistance, impact strength, machinability and fatigue life [10-17].

Large dendrites of primary α can be formed during solidification or homogenization of Zn-Al cast alloy. They deteriorate the mechanical properties or impact strength, [4] where it was found that the tensile strength increases with decrease of the dendrite arm spacing and elongation increases with decrease in grain size. This can be overcome by adding certain alloying elements of rare earth elements in small amount. Increase in the tensile and/or compressive strength of some Zn-Al alloys was achieved by adding 0.1% Ti, 0.02 to 1.0% of other elements such as Nb, Ta, V, Zr or other rare earth metals. Increase in the ductility of these alloys was achieved by addition of 0.1% B, and the vibration damping was greatly improved by addition of 0.05% to 1.0% Ti and/or 0.05% to 3.0% Zr, [6].

These improvements are certainly due to micro-structural changes occurring in these alloys. Improvement in mechanical properties of Zinc- base alloys for metal pattern by addition of some alloying elements was investigated by Motohashi et al [5]. They found that Zr as a grain refiner has no noticed effect on mechanical properties of Zn-Al alloys compared to the addition of Titanium.

The effect of addition of Ti-B on the microstructure of the ZA25 alloy was studied by Abdel-Hamid [7], in the range of 0.01% Ti - 0.002% B to 0.07% Ti - 0.014% B. The microstructure indicated fine petal-like grains of α instead of a coarse dendritic structure were formed. Also, it was found that grains of α refinement increased with increasing the addition rate up to 0.03% Ti -0.006% B beyond which it did not produce any further refinement. Increasing the addition beyond this level led to existence of massive TiAl3 crystals in the modified alloy [7].

Zhu [9] found that addition of Cu up to 2% has improved the tensile properties and creep resistance of the Zn-Al based al-

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- *Adnan I.O. ZAID is currently Professor Industrial Department Jordan University of Jordan. E-mail: adnan_kilani@tahoo.com* loys. The fundamental evaluations of both with microstructure and phase transformation of the alloy were believed to be of importance in understanding the mechanism associated with those mechanical properties. He also found that the lamellar structure has changed to spheroidized structure in the ruptured part, because of the concentrated high strain during creep, which enhanced the interfacial energy and resulted in segmentation of the lamellar structure and inter-dendritic region. In addition to microstructure change from lamellar structure to spheroidized structure, two phase transformations were observed during creep testing at 150oC [9].

Recently, Zaid and Alami [13] have studied the effect of vanadium addition to commercially pure aluminium on its grain size, hardness, and fatigue life. They found that adding 0.1% wt vanadium resulted in enhancement of grain refining efficiency of both the Al-Ti binary and the AL-Ti-B ternary master alloys. They also found that the addition of 0.1% wt to Al grain refined by Ti-B resulted in increase of its hardness. Furthermore, they found that addition of vanadium resulted in improvement of fatigue lives of both Al grain refined by Ti or by Ti-B at all stress levels.

Zaid and Al-Bana [14] have investigated the effect of addition of Zirconium on the same material, and found that the addition of Zirconium to Aluminium resulted in improvement of its hardness and mechanical behaviour. Also, they found that the addition of Zirconium of 0.1% to aluminium grain refined by Titanium or Titanium + Boron resulted in further improvement of fatigue life and strength in both cases.

Zaid and Al-Qawabah [15] have investigated the effect of Ti and Ti-B on the mechanical strength and fatigue life of ZA5. They found that addition of Ti has resulted in the deterioration of the fatigue life particularly at high stress levels, whereas addition of Ti-B resulted in enhancement of its fatigue life, being more pronounced at lower stress levels.

Recently the effect of addition of Zirconium to ZA5 alloy grain refined by Ti-B on its mechanical strength, ductility and fracture toughness has been investigated by Zaid and Al-Dous [11], and more recently, the same authors have investigated the effect of addition of Zr on the mechanical behaviour, ductility and fracture toughness of ZA5 alloy grain refined by Ti, [12]. They found that addition of Ti+B or Zr or Ti+B+Zr resulted in modifying the coarse dendritic structure of the ZA5 alloy into a fine nodular one and addition of one of these elements alone or together resulted in enhancement of the mechanical strength, hardness, ductility, toughness and impact strength of this alloy. Detailed review of the grain refinement of Zn-Al alloys is recently presented by Zaid [10].To the best of the authors' knowledge, the effect of addition of tantalum, Ta, on the fatigue life of ZA5 has not been previously reported. As this alloy is used in manufacturing parts subjected to cyclic loads in the automobile and aircraft industries e.g. tail gear box, cabin attachment brackets of body structure of helicopter and other parts, it is anticipated that it is worthwhile investigating the effect of Tantalum on the metallurgical and mechanical characteristics of ZA5. This formed the main objective of this research work in this paper.

2 MATERIALS, EQUIPMENT AND EXPERIMENTAL PROCEDURES

2.1 Materials

The base material used throughout this work is the commercial zinc-4.3% aluminium alloy with common trade name ZA5, having a melting point of 380-386^{o}C and a density of 6.6gm/cm^{3}. The chemical composition of this alloy by weight is shown in Table 1.

High purity aluminium 99.999% and tantalum powders were used for preparing the binary Al-2%Ta master alloy. Similarly high purity Zinc and aluminium were used to balance the weight percentage in preparing the different micro-alloys. Master and micro-alloys were prepared in graphite crucibles and graphite rods were used for stirring in all the experiments.

TABLE 1

CHEMICAL COMPOSITION OF ZINC ALUMINUM ALLOY, ZA5 (WT.%)

Element	Al	Cu	Mg	Fe	Pb	Cd	Sn	Zn
Wt. %	4.3	1.2	0.06	0.08	0.005	0.004	0.003	balance

2.2 Experimental Procedures

The experimental work was carried out in three steps: the first step was the preparation of the binary Al-Ta master alloy, the second step was preparing the different ZA5-Ta micro-alloys, with different Ta weight percentages and the third step was to prepare specimens from each micro-alloy for hardness, mechanical behaviour, fatigue tests and metallurgical examinations.

2.2.1 Preparation of the binary Al-2%Ta Master Alloy

The binary Al-2%Ta master alloy was prepared by replacing the predetermined amount of aluminium powder in a graphite crucible which was placed in a preheated electrical furnace at 1100^{o}C for 10 minutes, the crucible was taken out and the predetermined amount of the high purity.

Refractory metal, Ta, wrapped in aluminium foil, was added to the aluminium melt under a cryolite flux (NaF-AlF), stirred by the graphite rod for one minute and brought back to the furnace for 30 minutes. Finally, the crucible was taken out, stirred for one minute and spread over a thick cast iron plate to solidify into pieces of about 10 mm thickness. This master alloy was cut into small pieces to be used in preparing the different ZA5-Ta micro-alloys.

2.2.2 Preparation of The Different ZA5-Ta Micro-alloys

The different ZA5-Ta micro-alloys were prepared by melting the predetermined amounts of the ZA5 alloy and the balancing weight of zinc in an electric furnace at 750oC and kept at this temperature for 30 minutes, after which the predetermined amount of the ZA5-2%Ta master alloy wrapped in aluminium foil was added to the melt in the crucible and brought back to the furnace for 15 minutes and finally the crucible was brought out of the furnace, stirred for one minute and poured to solidify in thick brass hollow cylinders.

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Five different ZA5-Ta micro-alloys were prepared following the same procedure namely: ZA5-0.02%Ta, ZA5-0.04%Ta, ZA5-0.06%Ta, ZA5-0.08%Ta and ZA5-0.10%Ta.

Other specimens were also prepared from ZA5 and each micro-alloy to determine the hardness using Vickers HWDM-3 tester. An average of seven values on each micro-alloy was determined and considered to represent its hardness.

The mechanical behaviour for each micro-alloy was determined from the compression test performed in accordance with ASTM-E9 on specimens of 9mm diameter and 9mm height on Shimadzu-universal testing machine of 1000KN.

3 RESULTS AND DISCUSSION

As demonstrated in this document, the numbering for sections upper case Arabic numerals, then upper case Arabic numerals, separated by periods. Initial paragraphs after the section title are not indented. Only the initial, introductory paragraph has a drop cap.

3.1 Effect of Tantalum, Ta, Addition on Microstructure of ZA5 Alloy

It was difficult to determine the grain size of ZA5 and its alloys because there were no clear grain boundaries of these alloys. It contains different phases such as, inter-metallic compound, dendrite, and eutectic, as indicated by Fig.1.

Similarly, it was not possible to determine the grain size of the different ZA5-Ta micro-alloys for the same reason. However, the microstructure of these micro-alloys revealed that addition of 0.02%Ta, 0.04%Ta and 0.06%Ta resulted in partial changing of the microstructure from pure columnar into columnar and nodular as indicated by Figs.2, 3, and 4 respectively. Increasing Ta addition to 0.08% and 0.10% indicated some petals within the nodular structure as illustrated by the photo-micrographs of Figs. 5 and 6 respectively.

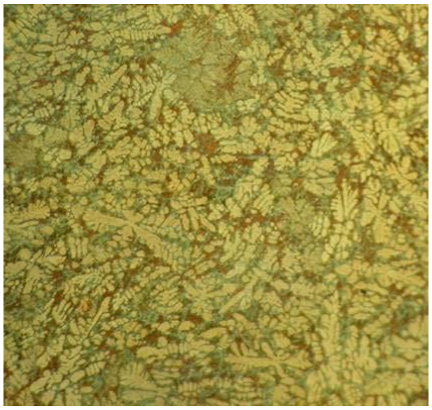

FiG. 1: Photomicrograph Showing the General Microstructure of ZA5, X200

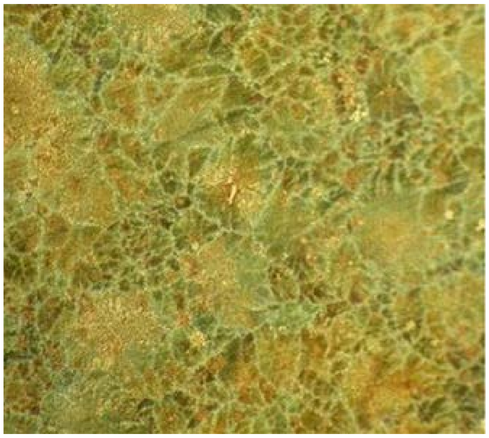

Fig. 2: Photomicrograph Showing the General Microstructure of ZA5-0.02%Ta, X200

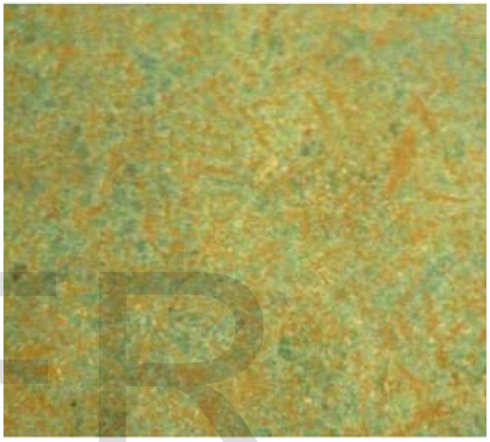

Fig. 3: Photomicrograph Showing the General Microstructure of ZA5-0.04%Ta, X200

Fig. 4: Photomicrograph Showing the General Microstructure of ZA5-0.06%Ta, X200

3.2 Effect of Ta Addition on the Hardness of the ZA5 Alloy

It can be seen from Fig. 7 that addition of Ta resulted in enhancement of micro-hardness of ZA5 alloy at all percentages. However, the maximum enhancement was achieved in the case of 0.04%Ta addition where the micro-hardness of this alloy was increased by 13.33% than ZA5. The minimum en-

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hancement was achieved in case of 0.10%Ta addition, being only 2.88% as shown in the histogram of Fig. 7 This increase in hardness is attributed to the change of structure from coarse dendritic structure to fine nodular and petal like structures. This is in general agreement with previous results when other refiners e.g. Zr was added to the same ZA alloy.

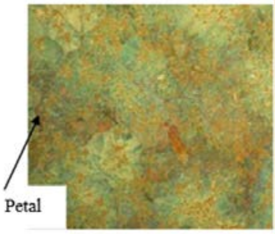

Fig. 5: Photomicrograph Showing the General Microstructure of ZA5-0.08%Ta, X200

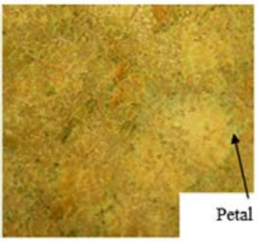

Fig. 6: Photomicrograph Showing the General Microstructure of ZA5-0.10%Ta, X200

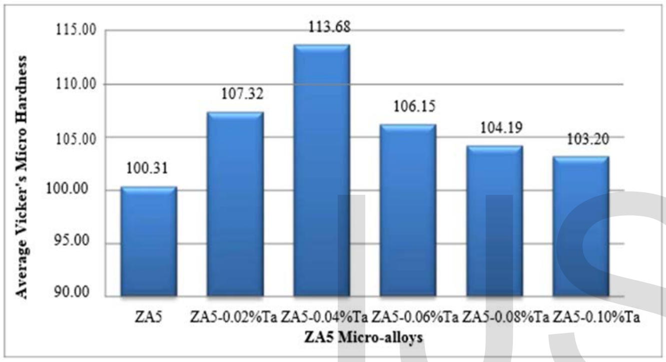

Fig. 7: Effect of Different Ta% addition on the Hardness of ZA5 alloy

3.3 Effect of Ta Addition on the Mechanical Behaviour of ZA5 alloys

The effect of addition of Ta on the mechanical strength of ZA5 is shown in Fig. 8. It can be seen from this figure that addition of Ta up to 0.06 % resulted in enhancement of its mechanical strength. Increasing the weight percentages of Ta beyond 0.06% resulted in deterioration of its mechanical strength, being more pronounced at 0.10%Ta addition where decrease of 4.32% in flow stress at 20% strain was obtained as shown in Table 2. Similarly, it can be seen in Fig. 9 that the compressive strength increases with increase of Ta addition up to 0.06 % beyond which the addition causes reduction in the flow stress.

The general equation representing the mechanical behaviour of ZA5 alloy together with the other mechanical characteristic is shown in Table 2, from which it can be seen that the work hardening index, n, of the ZA5 alloy by the addition of Ta up to 0.06% which results in decrease of its formability. Increasing the addition of Ta percentage to 0.08% and 0.10% resulted in increase of the work hardening index, n, of the ZA5 alloy which results in improvement of its formability.

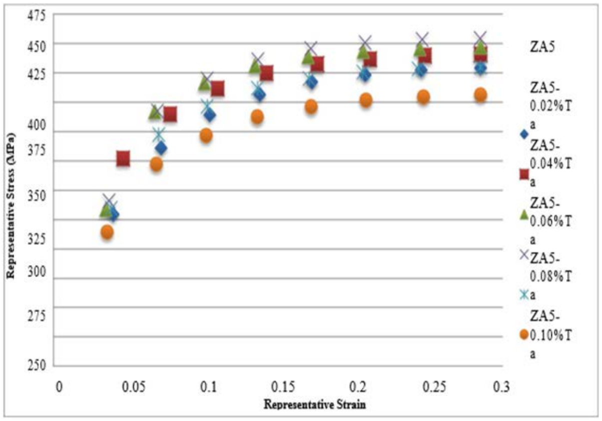

Fig. 8 : Representative Stress-Representative Strain for ZA5 Micro-alloys

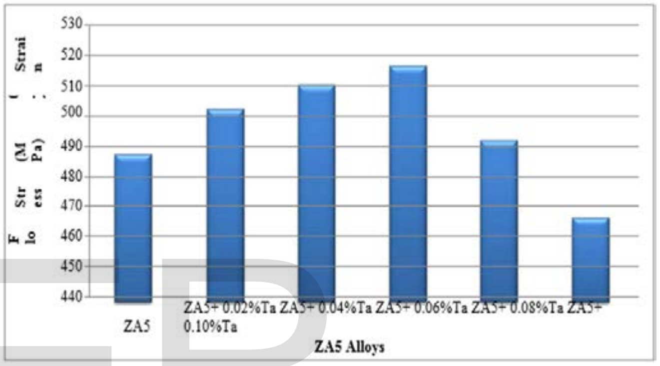

Fig. 9: Compression Flow Stresses for ZA5 and Its micro-alloys at 20% Strain

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TABLE 2

SUMMARY OF THE DIFFERENT CHARACTERISTICS OF THE MECHANICAL BEHAVIOR OF ZA5 AND THE DIFFERENT MICRO-ALLOYS

Alloy	Flow Stress (MPa) at 0.2 strain	Strength Coefficient *K* (MPa)	Work Hardening index *n*	General Equation of Mechanical Behaviour
ZAMAK 5	488.956	622.0995	0.1417	$\sigma = 622.0995\ .\varepsilon^{0.1417}$
ZA5 + 0.02%Ta	503.996	600.1022	0.1030	$\sigma = 600.1022\ \varepsilon^{0.1030}$
ZA5 + 0.04%Ta	512.028	645.4837	0.1365	$\sigma = 645.4837\ \varepsilon^{0.1365}$
ZA5 + 0.06%Ta	517.949	656.4851	0.1403	$\sigma = 656.4851\ \varepsilon^{0.1403}$
ZA5 + 0.08%Ta	493.397	614.6174	0.1297	$\sigma = 614.6174\ \varepsilon^{0.1297}$
ZA5 + 0.10%Ta	467.821	584.3499	0.1299	$\sigma = 584.3499\varepsilon^{0.1299}$

CONCLUSION

It is concluded from this work that addition of Ta to ZA5 at a Wt. % ranging from 0.02 to 0.10 resuited in:

i), changing its pure columnar structure of large grain size into columnar and nodular structure of finer grain size. Furthermore, increasing Ta addition to 0.08% and 0.10% indicated some petals within the structure.

ii). Enhancement of its Vickers micro-hardness.The maximum enhancement was in the case of 0.04%Ta addition where 13.33% was achieved, and the minimum enhancement was in case of 0.10%Ta addition, where only 2.88% increase was obtained.

iii). Enhancement of its mechanical strength up to 0.06 % addition. However, beyond 0.06% addition it resulted in deterioration of its mechanical strength, being more pronounced at 0.10%Ta addition where a decrease of 4.32% in flow stress at 20% strain was obtained.

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