Effect Of Rapid Solidification On Mechanical Properties Of Free Machining Lead Free Aluminum Alloys For Improved Machinability

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ABSTRACT

There have been very few reports describing the free machining lead free aluminum alloys containing minimal amounts of tin and indium melt spun process. Our paper describes the effect of fundamental factors on the machinability of free machining lead free aluminum alloys rapidly solidified from melt. Structural and thermal properties have been investigated by x-ray diffraction (XRD) and differential scanning calorimetry (DSC) techniques. Tensile test machine used in studies the mechanical properties such as ultimate tensile strength, elastic constants, yield strength and critical shear stress for Al-Zn-Sn-In alloys. It is noticed that mechanical and thermal properties attributed to fine grained structure, reduced levels of segregation and presence of new intermetallic compounds (IMC) such as AlZn and SnZn due to high casting rate by rapid solidification processes. The determination of mechanical properties was suggested to be attributed to the gradual increase of α-Al crystals. We evaluated the tensile properties using tensile test machine of the melt-spun ribbons at varied stress-strain rates to determine the underlying deformation mechanisms .Critical shear stress (CSS) was also calculated .It was found that it is equal to 9.29 GPa for annealed ribbons at 262 ^{0}C for 9 hrs. The results showed that several combination of tensile strength ,yield strength ,elastic moduli can be generated from Al- 0.1wt% Zn-1.5 wt% Sn- 1.63 wt% In alloys before and after heat treatment at (262 ^{0}C for 3,6,9 hrs) to meet the needs of free machining aluminum alloy applications.

Indexing terms/Keywords

Free machining alloys, rapid solidification, microstructure, mechanical properties.

1. INTRODUCTION

It is well known that metallic liquids are extremely unstable and crystallize almost immediately at temperatures lower than melting point. Since recorded history, practical metallic materials have been made by taking advantage of the crystallization principle; however, progress with this approach was severely limited because of the requirements of the thermodynamic equilibrium conditions as well as the necessity of translation and rotation symmetry. The use of materials with low specific weight is an effective way of reducing the weight of structures. Aluminum alloys are among the most commonly used lightweight metallic materials as they offer a number of different interesting mechanical and thermal properties. In addition, they are relatively easy to shape metals, especially in material removal processes, such as machining [1]. Machinability is a consideration in the materials selection process for automatic screw machine parts. The ease with which a metal can be machined is one of the principle factors affecting a product's utility, quality and cost [2]. Free machining aluminum alloys used for machining operations such as drilling, milling, turning, etc. This means that if the factors against the cutting tools are low then the melt-spun ribbons used in this work are easily machinable. These alloys typically include free machining constituents such as lead, tin, indium and bismuth for improved machinability. These constituents form low melting point compounds which readily soften or melt These constituents form low melting point compounds which readily melt or soften due to the friction heat created during machining[3].These elements have a limited solubility in the aluminum solid solution and form soft ,low melting phases supporting chip breakage and lubricate the tool. Generally ,chip breaking alloying elements have to show the following properties :(1) these elements are insoluble in the aluminum matrix , (2) have lower melting point in comparison to the aluminum , (3)don`t form intermetallic compounds with aluminum or other alloying compounds , (4) have a lower hardness than the aluminum matrix . Lead, bismuth, tin, indium and others meet all or partially these requirements [4]. During turning, an extensive plastic deformation occurs in the shear plane which causes the breaking of less ductile material [4]. Furthermore, generated heat due to the massive plastic deformation leads to thermal expansion of the inclusions against the aluminum matrix and thus vacancy defect building [5,6]. Additionally, inclusions should begin to melt at theses temperatures [7]. through the increased volume and by the edge effect generated tension ,the ductility of the material in the working zone causes the easy breaking of the chips[5,8-9].During machining, free-machining alloys generate small chips or curls which are easily collected and do not interfere with the machining process. It is essential that these free machining aluminum alloys form these small chips or curls for proper machining.

In brief, such small and short chips are substantial for a higher productivity and reduced cycle time, resulting in cost and time savings [10]. Therefore the current research paper focuses on chip breaking inclusions in machining aluminum alloys where lead is substituted by tin and indium.

2. EXPERIMENTAL PROCEDURES

The experiment used variations of free machining lead free aluminum alloys as used in table (1).

Table 1. Designated composition of the free machining lead free aluminum alloys

Free machining alloy	Element content (wt%)			
	Al	Zn	Sn	In
Al-Zn-Sn-In	99.48	0.1	0.2	0.22
Al-Zn-Sn-In	98.86	0.1	0.5	0.54
Al-Zn-Sn-In	97.88	0.1	1	1.02
Al-Zn-Sn-In	96.77	0.1	1.5	1.63

2.1. MATERIALS AND SAMPLE PREPARATION

Rapidly solidified Al-Zn-Sn-In alloys have been produced by a single copper roller melt-spinning technique [11]. Required quantities of the used aluminum, zinc, tin, indium metals of 99.999% purity were weighed out and melted in a porcelain crucible. After the alloys were molten, theme lt was thoroughly agitated to effect homogenization. The casting was done in air at a melt temperature of 660 ^{0}C. The speed of the copper wheel was fixed at 2900 rpm; which corresponds to a linear speed of 30.4 m/s.
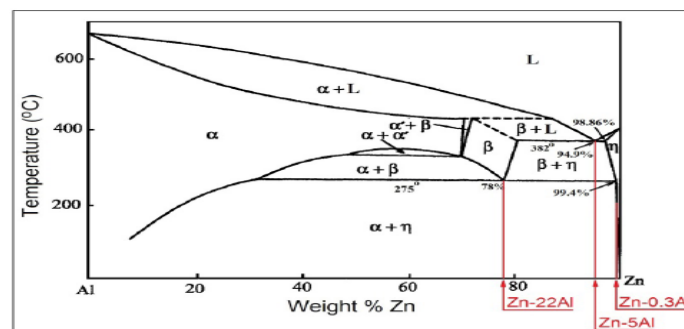

Fig 1: Binary Al-Zn phase diagram [12]

2.2. SAMPLE CHARACTERIZATION

A variety of techniques was carried out to characterize the crystallographic, and transformation features of the melt spun ribbons including x-ray diffraction. The x-ray diffraction study was carried out using Cu Kα radiation at room temperature. The microstructure analysis was carried out on a scanning electron microscope (SEM) of type (JEOL JSM-6510LV, Japan) operate at 30 KV with high resolution 3 nm. The melting temperature of these alloys was determined by differential scanning calorimetry, with a heating rate 10K/min [13].

2.3. MECHANICAL MEASUREMENTS

2.3.1. Tensile Test Machine

In tensile testing, sample to be tested is machined to standard dimensions. Generally 40 mm length and 2 mm width round test specimen as shown below is used for the test.

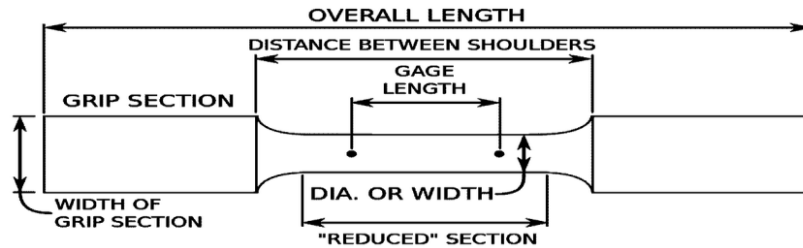**Photographic view**

Sample dimensions

Fig 2:Tensile test machine

The specimen is gauge marked with a center punch, scribe marks or drawn with ink. The purpose of these gage marks is to determine the elongation. The testing machine is equipped with a loading system of mechanical. The specimen is fitted in the laws of the testing machine and subjected to a tensile load. The applied load (stress) and the resulting elongation (strain) of the specimen are measured computerized. The process is repeated with increased load until the specimen breaks. Using these data a stress- strain diagram is plotted using computer set up contains software program to find out tensile properties.

2.3.2. Microhardness

Vickers Hardness Test is a standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indention is measured under a microscope and the Vickers Hardness value read from a conversion table Vickers hardness is a measure of the hardness of a material, calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter. Devised in the 1920s by engineers at Vickers, Ltd., in the United Kingdom, the diamond pyramid hardness test, as it also became known, permitted the establishment of a continuous scale of comparable numbers that accurately reflected the wide range of hardness found in steels.

The indenter employed in the Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136⁰. The diamond is pressed into the surface of the material at loads ranging up to approximately 120 kilograms-force, and the size of the impression (usually no more than 0.5 mm) is measured with the aid of a calibrated microscope. The Vickers number (H_V) is calculated using the following formula:

$$H_v = \frac{2F \sin\frac{136^0}{2}}{d^2} \quad , \quad H_v = 1.854 \frac{F}{d^2} \text{ approximately} \quad (1)$$

With (F) being the applied load (measured in kilograms-force), d the arithmetic mean of the two diagonals, d_1 and d_2 in mm and d^2 the area of the indentation (measured in square millimeters). The applied load is usually specified when H_V is cited.

3. RESULT AND DISCUSSION

3.1. Structure Properties

3.1.1. Structure

Metal alloys prepared using Rapid solidified from melt was reported by Pol Duwez et al [13]. The X-ray diffraction (XRD) patterns of the melt-spun Al-Zn-Sn-In ribbons rapidly solidified from melt at (660 ^{0}C). The X-ray analysis of the alloys show the existence of four kinds of phases the Al-phase with face centered cubic structure, $Al_{0.403}Zn_{0.597}$ with anorthic structure, In-phase with tetragonal structure and SnZn phase with hexagonal structure. From X-ray diffraction patterns of Al-Zn-Sn-In alloys as indicates show that two phases of the structure face centered cubic α-Al and intermetallic compounds $Al_{0.403}Zn_{0.597}$ at 2θ= 38.4662 , 44.6465, 65.0767 , 78.1715 ,82.3878 , 99.0322 of alloys as shown in Figures (3 ,4). From x-ray analysis, adding Sn and In content to Al-0.1wt% Zn alloy produced a change in its matrix microstructure (particle size, lattice parameters and lattice distortion) and the shape of formed phases such as peak intensity, peak broadness and peak position. A cubic crystal gives diffraction lines whose sin2θ values satisfy the following equation obtained by combining the Bragg law with the plane-spacing equation for the cubic system:

$$\frac{\sin^2\theta}{(h2+k2+l2)} = \frac{\lambda^2}{4a^2} \quad (2)$$

The lattice parameter **a** calculated from the sin2θ value for the highest-angle line, it was found approximately the same value (a=4.054 Å It is also indicated that the number of atoms / unit cell is the same approximately (3.8 atoms/ unit cell).

- 5157 - | P a g e
November 2017
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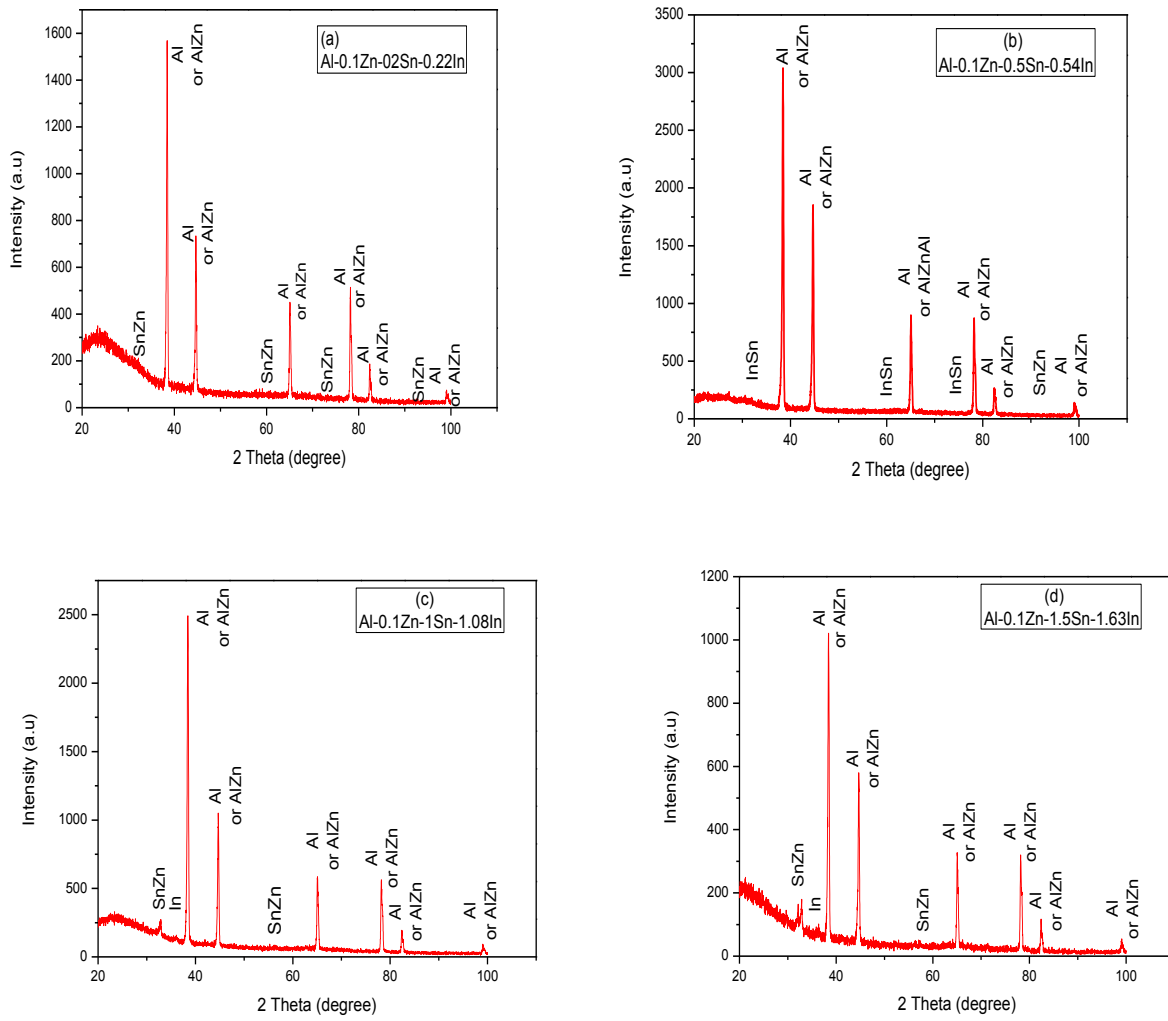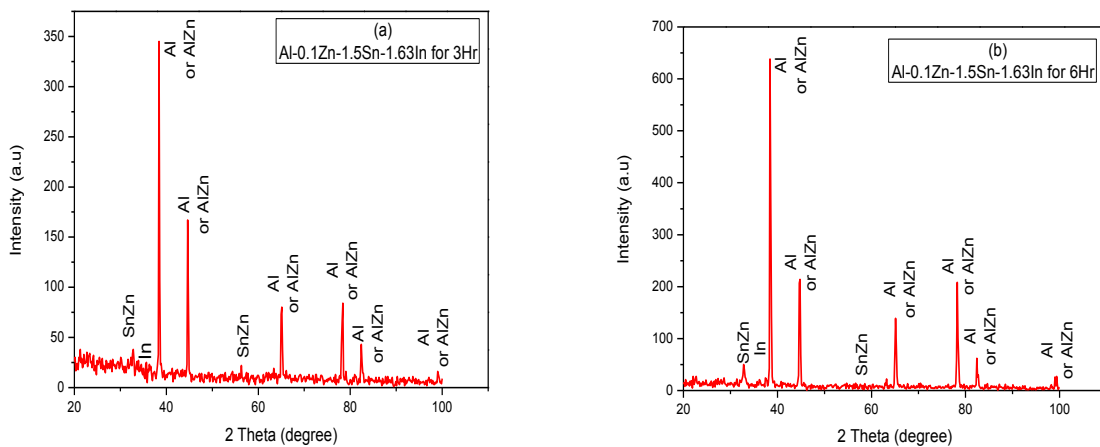J o u r n a l   o f   A d v a n c e s   i n   P h y s i c s

Fig 3: The XRD patterns of free machining (a) Al-0.1Zn-0.2Sn-0.22In, (b) Al-0.1 Zn-0.5 Sn-0.54 In,
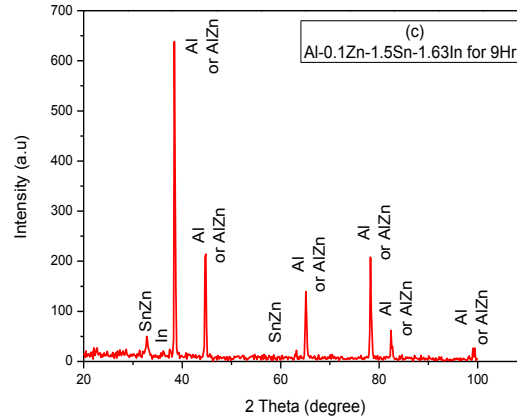(c) Al-0.1 Zn-1 Sn-1.08 In, (d) Al-0.1 Zn-1.5 Sn-1.63 In alloys

Fig 4: The XRD patterns of heat treatable free machining (a) Al-0.1Zn-1.5 Sn-1.63 In for 3hr, (b) Al-0.1 Zn-1.5 Sn-1.63 In for 6 hr, (c) Al-0.1 Zn-1.5 Sn-1.63 In for 9 hr alloys To determine information about the local lattice deformation and crystallite size (D_{eff}) in α- Al phases by the next formula [15]:

$$B = \frac{1}{D_{eff}} + 5 < \varepsilon^2 >^{1/2} \sin\frac{\theta}{\lambda} \qquad (3)$$

The $\frac{1}{Deff}$ and $5 < \varepsilon^2 >^{1/2}$ parameters are given in table 2(a, b), Lattice distortions for aluminum phase in all the melt-spun ribbons are very low as indicating in the table (2). This supports the optimum formation of face-centered cubic structure.

Table 2a. The details of the XRD analysis and lattice disorder of free machining aluminum alloys

| Melt-spun ribbons	Phases	Crystal system	a of Al phase (A^o)	Particle size (nm)	1/D_{eff} (A^{o-1})	$5 < \varepsilon^2 >^{1/2}$
Al-0.1%Zn-1.5%Sn-1.63%In (for 3 hr.)	Al AlZn ,SnZn, In	FCC Anorthic, Hexagonal, Tetragonal	4.05558	369.31	0.0022	0.000763
Al-0.1%Zn-1.5%Sn-1.63%In (for 6 hr.)	Al AlZn ,SnZn, In	FCC Anorthic, Hexagonal, Tetragonal	4.0558	325.48	0.0023	0.000916
Al-0.1%Zn-1.5%Sn-1.63%In (for 9 hr.)	Al AlZn ,SnZn, In	FCC Anorthic, Hexagonal, Tetragonal	4.0435	285.25	0.0027	0.001066

- 5159 - | P a g e
November 2017
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Table 2b. The details of the XRD analysis and lattice of free machining aluminum alloys

heat treatable alloys at 262°C

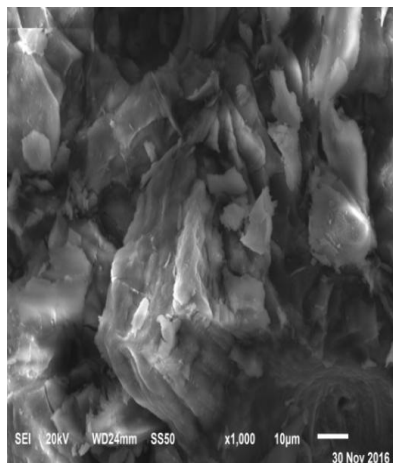| Melt-spun ribbons	Phases	Crystal system	a of Al phase (Å)	Particle size (nm)	1/D$_{eff}$ (A^{o-1})	$5 < \varepsilon^2 >^{1/2}$
Al-0.1%Zn-0.2%Sn-0.22%In	Al AlZn, SnZn	FCC Anorthic, Hexagonal	4.0535	276.21	0.0021	0.000813
Al-0.1%Zn-0.5%Sn-0.54%In	Al AlZn, SnZn	FCC Anorthic, Hexagonal,	4.0552	246.41	0.0028	0.00118
Al-0.1%Zn-1%Sn-1.02%In	Al AlZn, SnZn, In	FCC Anorthic, Hexagonal, Tetragonal	4.0547	281.99	0.0027	0.001161
Al-0.1%Zn-1.5%Sn-1.63%In	Al AlZn, SnZn, In	FCC Anorthic, Hexagonal, Tetragonal	4.0547	256.36	0.0023	0.000909

3.1.2. Microstructure Analysis

The microstructures of Al-Zn-Sn-In alloys before and after heat treatment are shown in figs (5, 6). As shown in fig (5a), the microstructure of free machining aluminum alloy Al-Zn-Sn-In is irregular grains. When the content of tin and indium increasing the crystal grains in fig 5 (b, c) are shaped long and short flakes like. With the content of tin and indium increasing more, the microstructure becomes finer as shown in fig (5d) and its distribution becomes more homogeneous. Fig 6 show the microstructure of free machining aluminum alloy Al-Zn-Sn-In after heat treatment at 262 ^{o}C at different times 3, 6, 9 hrs. As shown in fig 6 the IMCs of AlZn and SnZn phase (gray regions) begins to appear and increases evidently in the microstructure with time of heat treatment increasing. The finer and more homogeneous microstructure leads to suitable effect on the mechanical properties of free machining aluminum alloys.
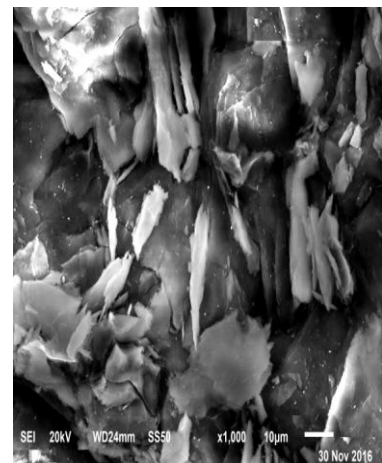
(a)	(b)	(c)
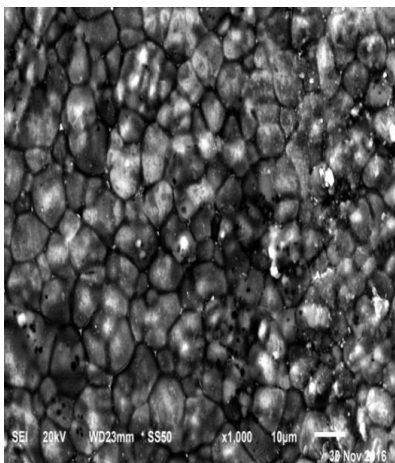
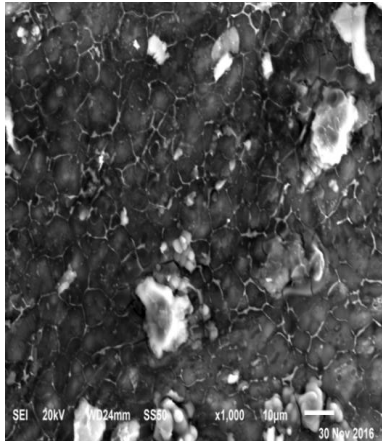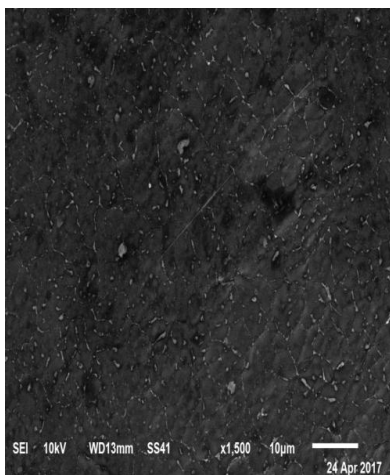| Al-0.1wt%Zn-0.2wt%Sn-0.22wt%In	Al-0.1wt%Zn-0.5wt%Sn-0.54wt%In	Al-0.1wt%Zn-1wt%Sn-1.02wt%In

(d)

Al-0.1wt%Zn-1.5wt%Sn-1.63wt%In

Fig 5: SEM micrograph of free machining (a) Al-0.1 Zn-0.2 Sn-0.22 In ,(b) Al-0.1 Zn-0.5 Sn-0.54 In ,

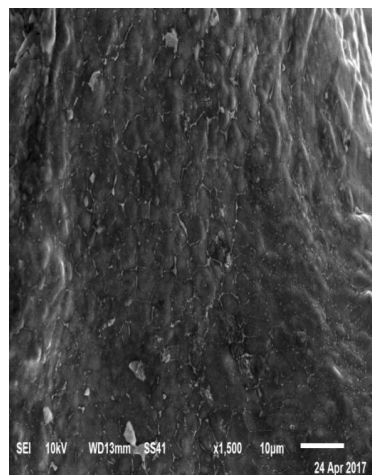**(c) Al-0.1 Zn-1 Sn-1.08 In, (d) Al-0.1 Zn-1.5 Sn-1.63 In alloys**

(a)	(b)	(c)

Al-0.1wt%Zn-1.5wt%Sn-1.63wt%In	Al-0.1wt%Zn-1.5wt%Sn-1.63wt%In	Al-0.1wt%Zn-1.5wt%Sn-1.63wt%In
(For 3 hr)	(For 6 hr)	(For 9 hr)

Fig 6 : SEM micrograph of heat treatable free machining (a) Al-0.1Zn-1.5 Sn-1.63 In for 3hr ,(b) Al-0.1Zn-1.5 Sn-1.63 In for 6 hr, (c) Al-0.1Zn-1.5 Sn-1.63 In for 9 hr alloys

3.2. Melting Behavior

Zu et al [16] suggested that structural changes take place to some extent in molten alloys as a function of temperature which have been confirmed by the corresponding calorific peak in a differential scanning calorimeter. The DTA curves obtained for alloys during heating with heating rate 10 K/min are shown in Fig. 7 (a, b). The figure for all prepared alloys shows a single endothermic peak corresponding to the melting reaction. From this figure the melting point (T_m), solidus temperature (T_s), liquidus temperature (T_l) and other thermal parameters (entropy ΔS, enthalpy ΔH, and specific heat C_p) of alloys are identified and then listed in Table (3).

- 5161 - | P a g e
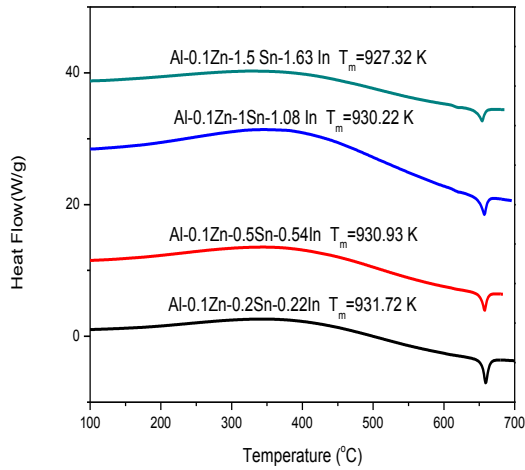November 2017
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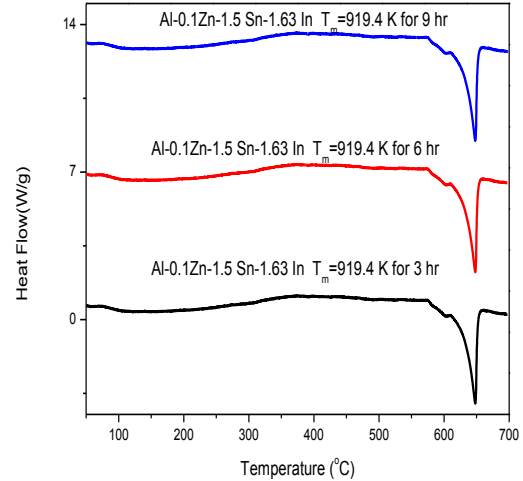**Fig 7a :Heating curves of free machining aluminum alloys**

Fig 7b :Heating curves of heat treatable free machining aluminum alloys at 262°C

Table 3a. Thermal analysis of free machining aluminum alloys

Melt-spun ribbons	T_m (K)	T_s (K)	T_l (K)	Enthalpy (j/g)	Specific heat C_p (j/kg.k)	Entropy change (j/g.k)
Al-0.1%Zn-0.2%Sn-0.22%In	931.72	926.42	950.37	208.5	8705.637	222.239
Al-0.1%Zn-0.5%Sn-0.54%In	930.93	924.29	942.44	125.9	6936.639	134.917
Al-0.1%Zn-1%Sn-1.02%In	930.22	921.39	942.29	171	8181.818	183.549
Al-0.1%Zn-1.5%Sn-1.63%In	927.32	917.79	943.66	120.9	4673.367	129.931

Table 3b.Thermal analysis of heat treatable free machining aluminum alloys at 262°C

Melt-spun ribbons	T_m (K)	T_s (K)	T_l (K)	Enthalpy (j/g)	Specific heat C_p (j/kg.k)	Entropy change (j/g.k)
Al-0.1%Zn-1.5%Sn-1.63%In (for 3 hr)	919.4	905.07	920.9	37.59	2374.605	41.181
Al-0.1%Zn-1.5%Sn-1.63%In (for 6 hr)	919.4	905.07	920.9	37	2337.334	40.534
Al-0.1%Zn-1.5%Sn-1.63%%In (for 9 hr)	919.4	905.07	920.9	37.1	2343.651	40.644

The enthalpy of the system is determined by bonding between atoms, and entropy is determined by assemblage of relative positions of the atoms of the melt-spun ribbons used in this work. From the results of the thermal analysis it was found that the enthalpy content decreased as the enthalpy decreased for Al-Zn-Sn-In melt-spun ribbons.

3.3. MECHANICAL MEASUREMENTS

3.3.1. Elastic Moduli And Tensile Properties

The tensile test machine is most frequently performed to determine mechanical properties. Information on various tensile properties like proportional limit, elastic limit, yield point, yield strength, ultimate strength and modulus of elasticity is given in our article. Using tensile test machine for drawing stress-strain characteristic curve to calculate tensile strength, yield strength and elastic moduli and then listed in Table (4).
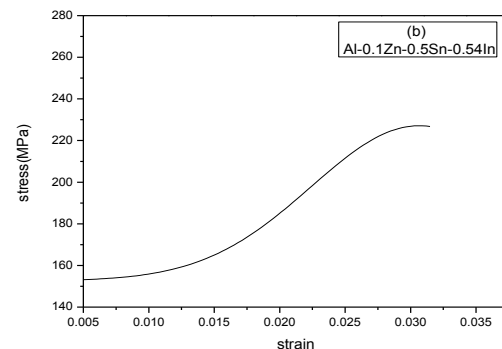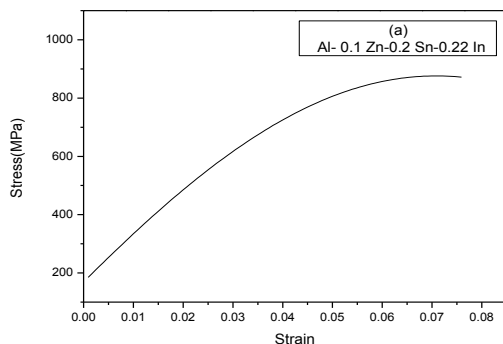
- 5162 - | P a g e
November 2017
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Table 4a. Experimental values of elastic moduli and tensile properties of free machining aluminum alloys

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Toughness (J/m³)	Critical shear stress CSS(GPa)	E (GPa)	G (GPa)	B (GPa)	H$_v$ (MPa)
Al-0.1%Zn-1.5%Sn1.63%In (for 3 hr.)	918	809.5	27.5	9.27	179.6	66.3	204.9	483.5
Al-0.1%Zn-1.5%Sn-1.63%In (for 6 hr.)	873	688.3	34.9	6.5	133.3	49.2	152.1	531.6
Al-0.1%Zn-1.5%Sn-1.63%In (for 9 hr.)	1200	1004.0	48.0	9.29	182.4	67.4	208.1	471.8

Table 4b. Experimental values of elastic moduli and tensile properties of heat treatable free aluminum machining aluminum alloys at 262 °C

Alloy	Tensile strength (MPa)	Yield strength (MPa)	Toughness (J/m³)	Critical shear stress (CSS) (GPa)	E (GPa)	G (GPa)	B (GPa)	H$_v$ (MPa)
Al-0.1%Zn-0.2%Sn-0.22%In	875	677.2	32.8	7.24	144.5	53.4	163.2	310.7
Al-0.1%Zn-0.5%Sn-0.54%In	262	206.5	4.3	4.3	78.8	29.1	89.2	319.4
Al-0.1%Zn-1%Sn-1.02%In	399.3	328.3	7.1	8.4	106.04	39.2	119.6	286.2
Al-0.1%Zn-1.5%Sn-1.63%In	777.8	672.3	26.6	8.32	161.8	59.8	184.6	254.02

Table (4.a) lists the relationship between composition of tin and indium and tensile properties. It is shown that small amounts of tin and indium have some effect on mechanical properties of free machining aluminum alloys which enhances the tensile properties. It is cleared that a presence of large amount α-Al rich phase causes the strengths resistant deformation increases. Consequently, the increase of resistant of deformation means the increase of strength. Also, Table (4.b) lists the relationship between composition of tin , indium and tensile properties of free machining aluminum alloys after heat treatment at 262 °C at different times 3, 6 and 9 hrs. It is clear that the tensile properties, especially UTS, toughness and H$_v$ are improved and enhanced to max value at 9 hrs. Mechanical properties of Al-Zn-Sn-In free machining aluminum alloy are improved due to fine dispersion strengthening mechanism (partial size is less than 1 μm) which will impede grain boundary movement.

- 5163 - | P a g e
November 2017
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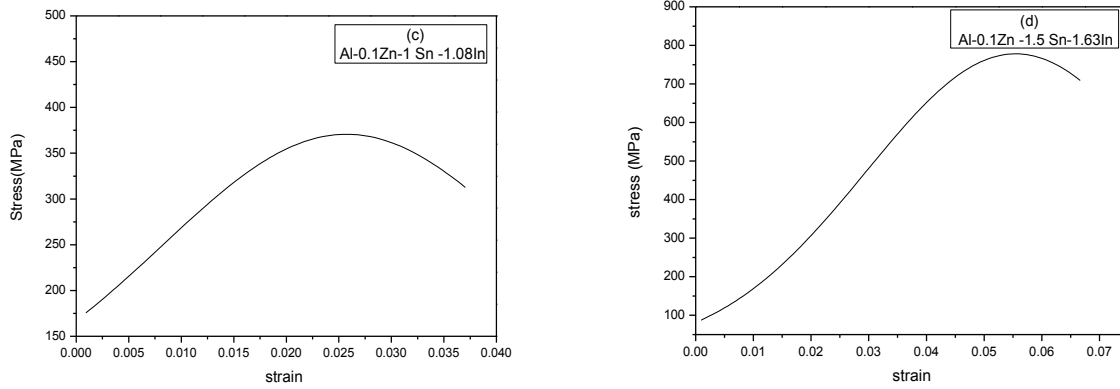J o u r n a l o f A d v a n c e s i n P h y s i c s

Fig 8: stress-strain characteristic curves of free machining (a) Al-0.1 Zn-0.2 Sn-0.22 In, (b) Al-0.1 Zn-0.5 Sn-0.54 In , (c) Al-0.1 Zn-1 Sn-1.08 In, (d) Al-0.1 Zn-1.5 Sn-1.63 In alloys
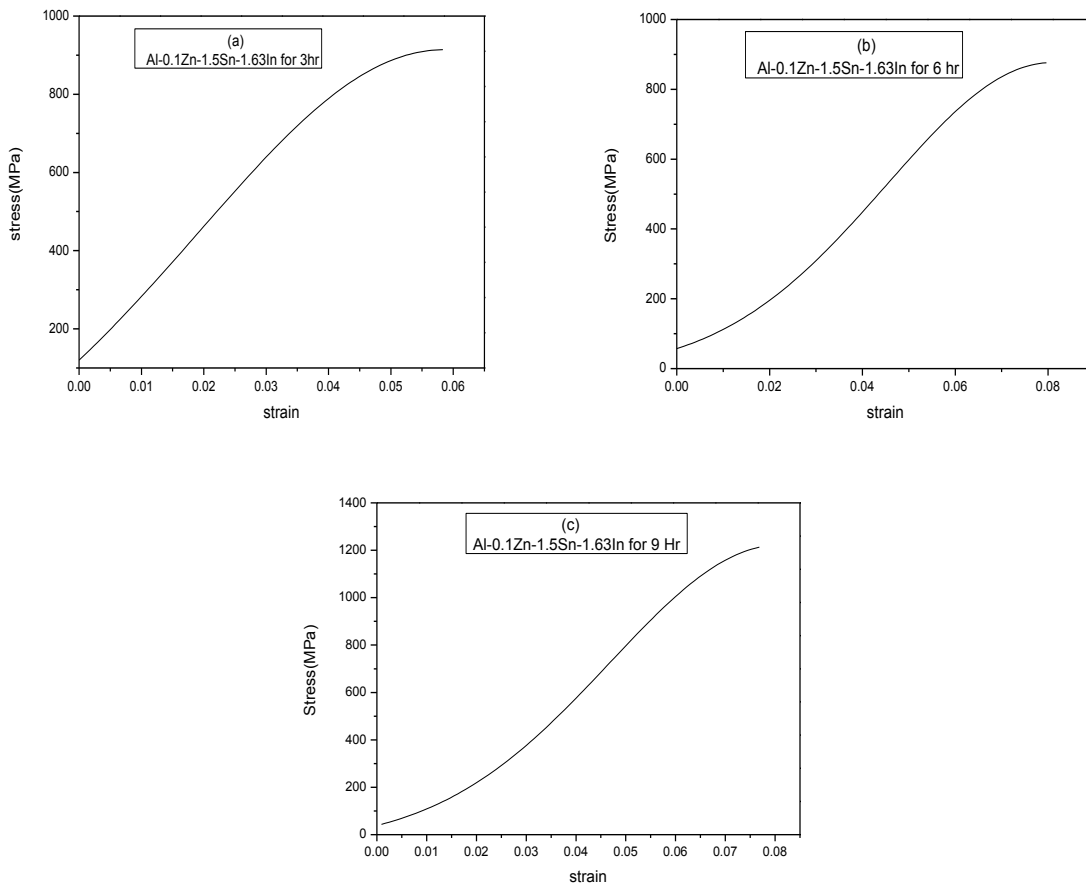

Fig 9: stress-strain characteristic curves of heat treatable free machining (a) Al-0.1 Zn-1.5 Sn-1.63 In for 3hr ,(b) Al-0.1 Zn-1.5 Sn-1.63 In for 6 hr,(c) Al-0.1 Zn-1.5 Sn-1.63 In for 9 hr alloys

The alloys after heat treatment transform from elastic-plastic behavior to plastic behavior showed in figure 8. From the elastic moduli and stress-strain diagram in figure (8, 9) for all melt-spun ribbons obtained in this research , the critical shear stress (the minimum shear stress required to begin plastic deformation or slip) which acting on the slip plane at which the lattice becomes unstable. That is, the plastic deformation begins when the shear stress attains the value of the critical resolved shear stress as shown in fig (8, 9).

3.3.2. Microhardness

The mechanical properties of Al-Zn-Sn-In melt spun alloys can be determined by Vickers micohardness utilizing the standard Vickers formula, depending on literature of preceding studies [17, 18]. Table (4) lists the Vickers microhardness

values of the melt spun Al-Zn-Sn-In alloys. The microhardness values increases as a result of dispersion strengthening. In addition, the hardness increases when the alloy is heated at 262 ^{O}C (i.e., due to formation of some precipitate from IMCs when heat treated. Also, the hardness increases as content of tin and Indium increases.

CONCLUSIONS

In this study, the structural, thermal, mechanical of the free machining Al-Zn-Sn-In ribbons rapid solidified from melt were investigated.

-The results showed that the melt spinning technique lead to enhancing the intermetallic compound formation (AlZn and SnZn).

- Lattice distortions for aluminum phase in all the melt-spun ribbons are very low. This supports the optimum formation of face-centered cubic structure. Such configuration is inherently of lower energy and thereby more stable than a purely random arrangement of atoms.

- With the content of tin and indium increasing more, the microstructure becomes finer and its distribution becomes more homogeneous. The finer and more homogeneous microstructure leads to suitable effect on the mechanical properties of free machining aluminum alloys.

- Mechanical properties of Al-Zn-Sn-In free machining aluminum alloy are improved due to fine dispersions strengthening mechanism (partial size is less than 1 μm) which will impede grain boundary movement.

-After heat treatment at 262 ^{o}C, it is clear that the tensile properties, especially UTS, toughness and H_v are improved and enhanced to max value at 9 hrs.

-Critical shear stress values increased after heat treatment because the IMCs of AlZn and SnZn phase begins to appear and increase evidently after heat treatment.

-The microhardness values increases as a result of dispersion strengthening. In addition, the hardness increases when the alloy is heated at 262 ^{O}C (i.e., due to formation of some precipitate from IMCs when heat treated). Also, the hardness increases as content of tin and Indium increases.

-Melting temperature slightly changed and enthalpy increased after heat treatment due to presence of some precipitates of indium in the matrix.

Low density, suppression mechanical properties make Al-Zn-Sn-In free machining aluminum alloy attractive for industrial applications.

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