Synthesizing and Hot Deformation Behavior of Novel Al-X Wt.% Zn Alloys for Advanced Casting Industries

S. Sivasankaran, Fahad Al-Mufadi, Osama M. Irfan

Abstract*: The present paper investigates the synthesizing routes and best method to explain the hot deformation behavior of novel Al-x wt.% Zn alloys (x = 0, 10, 20, 30, 40 and 50 wt.%). Based on several synthesizing routes, it was studied that the liquid metallurgy route followed by squeeze casting and extrusion is the best manufacturing method of the novel Al-Zn castings. These novel Al-Zn casting alloys would give more benefits as it possesses lower value of melting temperature; which is best suited for die-casting parts. To explore the mechanical behavior of Al-Zn castings, hot deformation studies by developing the processing map is best method by which complete information related to these alloys bahaviour could be obtained. From the literature, it was found that the hot workability behavior can be examined by developing the processing map using dynamic material modelling (DMM) and constitutive models (sine-hyperbolic Arrhenius kinetic rate equation). The step by step procedure to be followed for hot deformation analysis was explained in this work. From this analysis, the peak flow stress, stability region, instability region, power dissipation efficiency, activation energy and dynamic recrystallization region can be explored. In addition, as a pilot study related to these Al-Zn alloy, several castings, namely, pure Aluminium(Al), Al-10Zn, Al-20Zn, Al-30Zn, Al-40Zn, and Al-50Zn were successfully casted using electric furnace and then all these castings were squeezed followed by extruded to have improved densification. The hardness of casted samples was revealed that Al-40Zn casting exhibited a vicker's hardness strength (VHS) of 1326 MPa which was 4 times higher than pure Al.

***Keywords*: Al-Zn castings, liquid metallurgy route, hot workability test, Vicker's hardness.**

I. INTRODUCTION

In past two decades, Al based materials are playing important role to the world due to low in density and possess excellent corrosion resistance. Some components used in aerospace and automobile industries would need to have good castability characteristics and more in specific strength which can be easily obtained by Al-Si die-casting alloys [1-3]. However, these Al-Si alloys would produce flake like brittle Si phase after solidification in the structure which is main barrier in these die-casting alloys. Preventing of the formation of this unwanted brittle Si phase in die-casting alloy is inevitable in the casting industries [4]. In addition, heat treatment (T6) must be carried out to improve its mechanical strength (> 300 MPa) in these die casting products [5, 6]. The secondary process like this heat treatment would increase the production cost consequently decreases the productivity in Al casting industries. Based on the present issues, it is mandatory to determine a new and novel alloy which should overcome these problems in die casting industries and to find an alternative novel manufacturing technique that should ensure higher strength even during casting conditions. It was found in 7xxx series Al alloys that the presence of Zn content ranges from 4% to 7% would contribute more in strength which is being used in aircraft parts and structural parts [7]. The observed higher strength in these 7xxx series alloys (around 4 GPa) are due to metastable Zn and Mg elements after aging [8]. However, this 7xxx series Al alloys can be recommended for die-casting applications as these 7xxx series alloys possess poor in castability. In the meantime, Al-Zn based alloys called as ZA 27 has more features interms of castability, higher value of mechanical strength with considerable ductility and outstanding wear resistance properties [9]. The castability of castings can be improved one more way of adding copper (Cu, <3%) into Al alloys, but, the dimensional stability would be affected due to $CuZn_4$ phase (ε phase) that diminish its applications [10]. Alemdağ et al [11] have examined the tribological and mechanical performance of Al-40Zn-3Cu alloy which was manufactured by gravity cast method. These alloys had possessed excellent wear resistance and outstanding mechanical properties. These alloys had exhibited tensile yield strength of 0.4 GPa with strain of more than 5% [11-13]. The melting point of Al-Zn alloy would be considerably decreased when the percentage of Zn is greater than 20 wt.% which would be very low value when compared to conventional die-cast Al alloys. Further, good solidification can also be obtained in Al-Zn alloys which can be conformed via Al-Zn phase diagram [14]. In addition, more content of Zn in Al would give more benefits in terms of increases the life of the products, decreases the melting time and temperature which would save the cost considerably.

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II. LITERATURE REVIEW

As per several literatures, Al-Zn alloys can be best suitable for die casting applications which could ensure more mechanical strength compared to other alloys. This section describes the detailed literature related to the present work.

Park and Kim [15] have developed the processing maps in as casting condition of Al-Zn-Mg-Cu alloy which is one kind of 7075 alloy, studied its deformation mechanisms and then finally compared the results with 7075 Al bulk alloys. The authors had taken the temperature ranges from 300ºC to 500ºC and used strain rate (SR) from 10^{-3} to 10^{-1} s^{-1}. It was found that similar crystallite size and deformation results were obtained in both cast and bulk 7075 alloys. Further, the authors revealed that the as casted samples were exhibited more efficiency in power and more stable zone as compared to bulk 7075 alloy. This was attributed to $MgZn_2$ second phase precipitates that was in the form of dendritic in the casted microstructure. Finally, the authors were concluded that the as-casted 7075 Al alloy had produced improved mechanical performances during hot working condition. Dong et al [16] had developed the mapping behavior in the alloy of Al-Mg-Si by hot compression tests. The authors were used Arrhenius equation using stress-strain data and then developed the mapping behavior using DMM eventually the best processing parameters were determined. Gangolu et al [17] had investigated hot deformation study on A356 alloy and A356+5 wt.% B_4C composites. They had varied the temperatures of 743K, 773K, 803K and 843K and used different SRs (10^{-3}, 10^{-2}, 10^{-1} and $1s^{-1}$). The authors had established the constitute relationship and determined various materials constants. In addition, they have found the stable and unstable region based on processing map results. Their results were revealed that the temperature region of 783 K to 843K and the SR region of 10^{-2} to 10^{-1} s^{-1} were instability domain and these regions were not suitable for hot deformation. Lianggang et al [18] had conducted isothermal compression test on AA 7075 alloy and examined the true stress-strain curves. The authors had conducted the tests with the temperature ranges from 573K to 773K and used SR from 0.01 to 10 s^{-1}. The authors had examined the hot deformation study (using Gegel and Murthy equations) and had exhibited good prediction results. Du et al. [19] investigated hot deformation study on Ti-47.5Al-Cr-V in as-extruded condition with temperature of 1373K and 1523K and used SR from 0.001 s^{-1} to 1 s^{-1}. It was found that the observed flow stress results had a positive with respect to SR whereas negative with respect to deformation temperature. Further, the authors had determined the activation energy and developed a constitutive model eventually the optimum processing parameters were found.

III. THEORETICAL BACKGROUND OF HOT DEFORMATION STUDIES

The constitutive equations and mapping behavior of material (modeling) are to be constructed by the following expressions.

Constitutive equations for Prediction of flow stress:

The results obtained from stress-strain data after compression by varying SR and temperature are to be used to find various constant for which the Arrhenius equation as mentioned in Eq. (1) is to be used [20].

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)^n\right]e^{(-Q/RT)} \quad for\ all\ \sigma \tag{1}$$

Here, $\dot{\varepsilon}$ is the applied SR, T is the temperature in K, R is the gas constant (8.314 J/molK^{-1}), σ is the flow stress in MPa obtained from experiments, Q is the activation energy in KJ/mol, and A, n and α are various constants. Hence, the Eq. (1) can be written at lower amount of stress level which is called as power law, and the value of higher stress level which is called as exponential function as Eqs. (2) and (3):

$$\dot{\varepsilon} = A_1\left(\sigma^{n1}\right) \tag{2}$$

$$\dot{\varepsilon} = A_2\left(e^{\beta\sigma}\right) \tag{3}$$

where the value of A_1 and A_2 can be obtained based on flow stress data which would indicate the material constants. These values are all independent with the value of flow stress and the value of temperature. Further, the equations (2) and (3) can be modified after taking logarithm on both sides as below:

$$\ln\sigma = \frac{1}{n_1}in(\dot{\varepsilon}) - \frac{1}{n_1}in(A_1) \tag{4}$$

$$\ln\sigma = \frac{1}{\beta}in(\dot{\varepsilon}) - \frac{1}{\beta}in(A_2) \tag{5}$$

The equations (4) and (5) would give us the predicted floe stress and the SR. The slope value of ln($\dot{\varepsilon}$) Vs ln(σ) and ln($\dot{\varepsilon}$) Vs σ curves would give the constants values of n_1 and β by linear fitting technique.

Then, α (MPa^{-1}) = β/n_1.

Moreover, the kinetic equation obtained from Arrhenius hyperbolic sine function had been used by Sellers and Tegart [20] which gives good predicted results based on Zener-Hollomon [21] parameters of "Z" and "σ". The parameter of "Z" of Zener – Hollomon would indicate the effect of SR during high temperature deformation study on flow stress curves which can be obtained as:

$$Z = \dot{\varepsilon}e^{(Q/RT)} \tag{6}$$

Sellers and Tegart [8] had developed an equation (7) which give the relation between Hollomon parameter and flow stress as:

$$Z = A\left[\sinh(\alpha\sigma)\right]^n \tag{7}$$

Further, the above equation [7] can be written as eq. (8) [22] which relates the flow stress (σ) and Z (parameter) as:

$$\sigma = \frac{1}{\alpha}in\left[\left(\frac{Z}{A}\right)^{1/n} + \sqrt{\left(\frac{Z}{A}\right)^{2/n} + 1}\right] \tag{8}$$

By comparing the two equations of Eq. (6) and Eq. (7) in all levels of stress values, new equation can be developed as Eq. (9) which relates the SR, stresses and T:

$$\dot{\varepsilon} = A\left[\sinh(\alpha\sigma)^n\right]e^{(-Q/RT)} \tag{9}$$

The amount of plastic deformation capability can be determined by the value of activation energy of Q using Eq. (9):

$$Q = R\left[\frac{\delta \ln \dot{\varepsilon}}{\delta n[\sinh(\alpha\sigma)]}\right]_T \left[\frac{\delta n[\sinh(\alpha\sigma)]}{\delta(1/T)}\right]_{\dot{\varepsilon}} = Rn's \qquad (10)$$

The equation (10) would give the strain rate sensitivity further based on its right side function which can be obtained from a graph drawn between δ lnέ versus δ ln[sinh (ασ)], the term δln[sinh (ασ)]/δ(1/T) would indicate the temperature sensitivity which can be obtained from a graph drawn between δ ln [sinh (ασ)] versus (1/T). In addition, the logarithmic transformation (Eq. (7)) is re-written as:

$$\ln Z = in A + n \ln[\sinh(\alpha\sigma)] \qquad (11)$$

Here, Z, α and σ are to be substituted in Eq. (11), and a graph is to be drawn (ln Z Vs ln [sinh (ασ)]) using linear regression. Now the values of 'n' and 'A' can be foundout. Based on the values of A, α, n and Q in Eq. (9) at all σ condition, a constitutive model can be developed for the SR which used to determine the σ of the material.

Establishment of processing maps using DMM:

Based on Prasad et al. [23], the development of processing maps for any materials would indicate the response of material against hot compressive deformation with respect to different strain rates and temperature consequently the variation occurs in the material microstructures. The variation in microstructural observation can be used to determine the optimum process parameters for doing hot deformation which can be well suitable for metal forming industries. Further, the DMM has to be used to construct the processing maps [24]. The constitution can be written as Eq. [12] which is based on at constant T and ε:

$$\sigma = K\dot{\varepsilon}^m \qquad (12)$$

The total power in the material during its plastic deformation for the given strain and temperature can be determined as:

$$P = \sigma\dot{\varepsilon} \qquad (13)$$

This total power would consist of two parts which are mentioned in Eq. (14) in the form of integrals as:

$$P = \sigma\,\dot{\varepsilon} = \int_0^{\dot{\varepsilon}} \sigma\, d\dot{\varepsilon} + \int_0^{\sigma} \dot{\varepsilon}\, d = G + J \qquad (14)$$

From the Eq. (14), the first part of integral would give the value of constant "G" and the second part of integral would give the value of "J" which is a co-content. Further, the area under the curve constructed based on constitutive equation would give G whereas the area of the curve (upper one) would give the J. According to Malvern [25], the value of G would indicate the amount of power dissipation due to temperature variation whereas the value of J would indicate the amount of power dissipation due to metallurgical processes. Gegel et al. [26] had examined that the power dissipation between G and J can be controlled by metal flow behavior which can be found by SR sensitivity (m) from the σ curves as:

$$m = \frac{dJ}{dG} = \frac{\dot{\varepsilon}\, d\sigma}{\sigma\, d\dot{\varepsilon}} \cong \frac{d\log\sigma}{d\log\dot{\varepsilon}} \qquad (15)$$

The value of strain rate sensitivity (m) would varies non-linear manner based on temperature changes and SR given. The value of J content is also a non-linear which can also be obtained as below:

$$J = J_{max} = \frac{\sigma\dot{\varepsilon}}{2} \qquad (16)$$

Based on the value of J and J_{max}, the power dissipation efficiency (η) can be determined as dimensionless parameters of η by eq. (17):

$$\eta = \frac{J}{J_{max}} = \frac{2m}{m+1} \qquad (17)$$

The changes in the η with the function of T and SR would constitute the processing map which shows various zones where different microstructural mechanism can be studied and investigated for the tested material. Further, from this map, several atomistic mechanisms such as discontinuous reception (DRX), dynamic recovery (DRY), super plasticity etc…and some thermodynamics concepts can be explored. Based on Ziegler [27], the ξ(έ) (instability parameter) can be examined with the function of temperature and SR which would give instability processing map. Using this instability processing map, metallurgical instability point due to plastic flow of material can be found out as Eq. (18).

$$\xi(\dot{\varepsilon}) = \left[\frac{\delta \ln(m/m+1)}{\delta \ln \dot{\varepsilon}}\right] + m \le 0 \qquad (18)$$

Computational method for instability parameter and power dissipation efficiency:

The third-degree polynomial equation results obtained from σ data with the function of SR and temperature would give the value of the *ξ(έ)* and the *η* (power dissipation efficiency). The connection among σ and έ in terms of logarithmic function is mentioned in Eq. (19) as:

$$\log\sigma = a + b\log\dot{\varepsilon} + c(\log\dot{\varepsilon})^2 + d(\log\dot{\varepsilon})^3 \qquad (19)$$

Here, the values of a, b, c and d would indicate the materials parameters. Further, the value of SR sensitivity (m) can be determined by substituting the Eq. (19) to Eq. (15) as:

$$m = \frac{d(\log\sigma)}{d(\log\dot{\varepsilon})} = b + 2c\log\dot{\varepsilon} + 3d(\log\dot{\varepsilon})^2 \qquad (20)$$

Based on the value of SR sensitivity (m) with temperature and SR, the η can be determined based on Eq. (17). In addition, the ξ (έ) can be obtained by substituting the Eq. (20) to Eq. (18) as mentioned in Eq. (21):

$$\xi(\dot{\varepsilon}) = \left[\frac{\delta \ln(m/(m+1))}{\delta \ln \dot{\varepsilon}}\right] + m = \frac{2c + 6d(\log\dot{\varepsilon})}{m(m+1)\ln 10} + m \qquad (21)$$

IV. MATERIALS AND METHODS

The commercially available Al and Zn ingots were purchased with purity of more than 99%. The chemical composition are given in Table I. According to the composition, both Al and Zn ingots are weighed and then, put inside the graphite crucible.

Here, the Zn ingots were mixed with Al ingots with weight percentage starting from 0 to 50. After charging the ingots as per Table 1, the graphite crucible was put inside an electric furnace (Nabatherm, Germany, maximum temperature 1000°C). The temperature during heating was set at 720°C with a series of steps to avoid thermal mismatching of both metals. First, both ingots were heated upto 400°C with a heating rate of 10°C per minute, and hold it for 45 minute. Then, the temperature was set to increase upto 720°C with the same heating rated, and hold it for 1 hr. Then, the melt was poured into a cylindrical mold by gravitational force. The solidified cast were melted three times again using the same procedure to achieve homogeneous alloy. In the last run, after pouring the melt into the mould, the high temperature cast was squeezed by a hydraulically operated ram with a pressure of 150 MPa. It was ensured the temperature around 550°C during squeezing. The schematic of showing the preparation of Al-Zn castings inside the electrical furnace and squeeze casting is shown in Figure 1. After squeeze casting, the samples were extruded with the extrusion ratio of 2:1 at 400°C in a 150 ton capacity hydraulic press. Figure 2 shows the photograph of extruded samples. The squeeze cast samples were cut into 15 x 15 x 15 mm size; ground it using different graphite sand papers with different grades, and polished it using Al_2O_3 lapping paste. Then, the Vicker's hardness test was conducted on the polished samples with the applied load of 1kg. The hardness was carried out in several places to check the homogeneity of the synthesized alloy. The average was used for investigation.

Table I. The chemical composition of synthesized Al-x wt.% Zn alloys

Sample composition	Weight of Al, g	Weight of Zn, g
Pure Al	1000	--
Al-10Zn	900	100
Al-20Zn	800	200
Al-30Zn	700	300
Al-40Zn	600	400
Al-50Zn	500	500

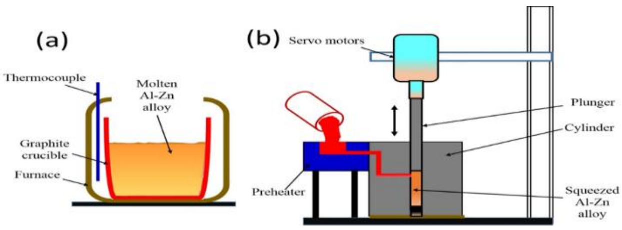

Figure 1. The diagram depicting (a) Preparation of novel Al-Zn alloy inside electric furnace (b) Squeeze casting set-up

Figure 2. Photographs of Squeeze cast followed by extruded Al- xwt.% Zn castings

V. RESULTS AND DISCUSSION

The mechanical behavior in terms of Vicker's hardness strength was carried out and the same is illustrated in Table II and Table III. Figure 1 shows the changes in Vicker's hardness strength at 10 different places of each sample. From Figure 1, it was confirmed that there was no much variation of observed strength which indicated the achievement of homogeneity through the present method. Further, from Figure 1, it was understood that the observed hardness strength has started to jump in a drastic manner up to the addition of 30 wt.% Zn metals in the Al. After that there was not much increment. The Al-30Zn casting alloy has produced around 1320 MPa strength which is very high value that can be applied for die-casting industries.

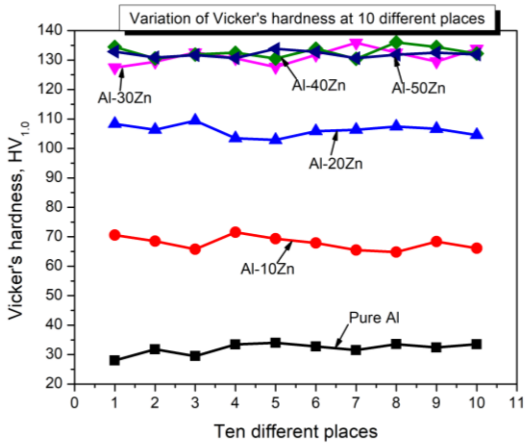

Figure 3. Measured Vicker's hardness values distribution at 10 different places

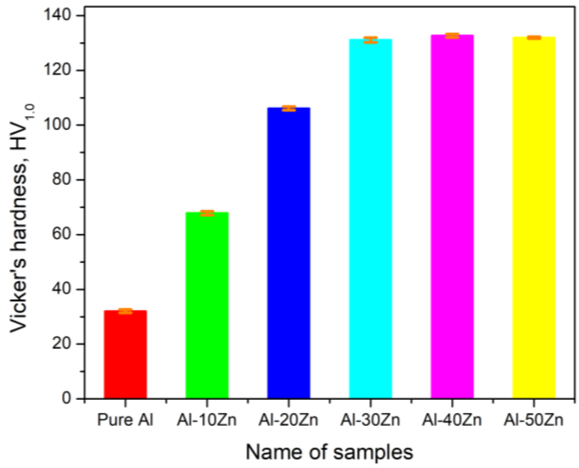

Figure 4. Average Vicker's hardness strength with error bar for Al-x wt.% Zn casting alloys

In order to examine the incremental behavior of Vicker's hardness strength with the Zn content in Al, Figure 2 is also drawn. The average hardness value was 320 MPa, 680 MPa, 1060 MPa, 1310 MPa, 1320 MPA, and 1329.6 MPa for pure Al, Al-10Zn, Al-20Zn, Al-30Zn, Al-40Zn, and Al-50Zn respectively. The strength of the developed castings was increased drastically by increasing the Zn content in the pure Al system up to 30 Zn.

Further addition of Zn content beyond 30wt.%, there was no changes in the strength due to non-uniform mixing and some casting defects might have formed in the casting. Therefore, from the several castings, namely, pure Al, Al-10Zn, Al-20Zn, Al-30Zn, Al-40Zn, and Al-50Zn, Al-30Zn casting has produced more strength which can be recommended for fabrication of die-casting parts in the modern casting industries.

Table 1I. Variation of Vicker's hardness value at ten different places of fabricated castings

Sample Composition	Vicker's Hardness values at different places of synthesized castings, $HV_{1.0}$									
	1	2	3	4	5	6	7	8	9	10
Pure Al	28	31.78	29.5	33.45	34	32.76	31.5	33.56	32.4	33.5
Al-10Zn	70.56	68.54	65.8	71.54	69.35	67.89	65.5	64.78	68.38	66.13
Al-20Zn	108.35	106.36	109.45	103.45	102.89	105.85	106.34	107.45	106.67	104.56
Al-30Zn	127.45	129.45	132.56	130.6	127.67	131.8	135.89	132.5	129.5	133.8
Al-40Zn	134.45	130.56	131.89	132.5	130.5	133.89	130.4	136	134.45	132.2
Al-50Zn	132.9	130.89	131.7	130.65	133.8	132.78	130.65	131.85	132.54	131.89

Table III. Statistical analysis of observed hardness values of Al-x wt.% Zn castings

Sample Composition	Average	Standard deviation	Standard error	Average ±error, $HV_{1.0}$
Pure Al	32.045	1.945132	0.615105	32±0.62
Al-10Zn	67.847	2.262668	0.715519	68±0.72
Al-20Zn	106.137	2.063024	0.652385	106±0.65
Al-30Zn	131.122	2.696309	0.852648	131±0.85
Al-40Zn	132.684	1.946057	0.615397	133±0.62
Al-50Zn	131.965	1.050896	0.332323	132±0.33

VI. CONCLUSION AND FUTURE SCOPE

In this work, pure Al incorporated with different weight percentage of Zn alloys were manufactured successfully by casting route (liquid metallurgy process). The addition of Zn metal was varied from 0 to 50 with a step of 10 wt.%. At most care was taken during synthesizing of various castings. The hardness of all casting was determined using Vicker's method. It was found that Al-30Zn cast has possessed improved strength which is recommended for dis casting parts. In addition, various step-by-step of hot deformation analysis using several equations were also explained. This hot deformation analysis is being analyzed by the research groups and it will be published shortly.

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