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Prediction of Hardness, Yield Strength and Tensile Strength for Single Roll Melt Spinning of 5083 Al-alloy Ribbons

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Abstract

In this paper, an empirical model is applied to predict the hardness, yield strength, and tensile strength of rapid solidified ribbons. The discovered empirical equation is obtained depends upon the experimental results of rapid solidification process for 5083 Al-alloys. The empirical equations predict values and describe the behavior of ribbon with consideration of ribbon thickness, grain size, hardness, yield strength, and tensile strength. The experimental work involves difference operation conditions and the results indicate that orifice diameter, nozzle roll wheel gap, and melting temperature have direct impact on the quality of alloy. Additionally, the results showed that there is a good agreement between experimental and predicted values where the correlation coefficient is 0.99. The experimental show that there is a possibility to produce very thin ribbons with thickness in micrometer by reducing the distance between nozzle and roll wheel, and reduce the orifice diameter of casting. The hardness, and yield strength increased due to increasing the number of small grain size in the ribbons structure and rapidly heat transfer of the small ribbons thickness. Moreover, the optimal melting temperature of this alloy is 925ºC which produces high ribbon hardness compared with other melting temperature that used in this research.

Keywords: Rapid solidification; Melt spinning; Ribbons; Empirical model; Mechanical properties

Introduction

Most metallic materials are produced from their liquid state. It is very important to understand their solidification path and the resulting microstructures which can be significant affected by melt undercooling [1]. Rapid solidification technology is an important process for the development of the advance metallic materials. It is a means to produce new alloys with superior properties and develop unusual even novel microstructure, which frequently exhibit beneficial properties. The process has direct impact on the properties of alloys. It is improved the mechanical properties and refining the microstructure [2].

Rapid solidification process is a tool for modifying the microstructure of alloy which is applied to produce a metallic glass with better mechanical and microstructure properties compared with those of conventional casting. Yield stress and hardness of bulk metallic glasses can be twice as these of steel [3]. The hardness of rapid solidified ribbons increases with decreasing thickness of ribbons which becomes more than twice of the original hardness of alloy before rapid solidification process because it produces homogenous structure with massive Nano grain size. It has one of the highest melt cooling rate among all continuous casting process because the solidification time and movement of the melt and substrate are very short [4].

Rapid solidification technique with one roller melt spinning technique is an important method that used to produce bulk metallic glasses materials nowadays. In this technique, a stream of molten metal is directed at a rapidly moving substrate. The final product is in the form of ribbon with thickness in micrometer. Quenching on the inside or outside of a rapidly rotating cylinder now appears to be a widely utilized technique and production rate of 2000 m/min obtainable [5].

Bogno have been studied characterization of rapidly solidified metallic alloy using combination of experiments and modelling [1]. Kramer et al. investigated various melt pool characteristics and their influence on the melt spun ribbon using high speed digital imaging. They showed that ribbon thickness can be computed depending on the density, viscosity, and melt stream diameter [6]. Tayebeh et al. have been studied the effect of cooling rate during melt spinning of fine ribbons. They use curve fitted with a correlation factor of 0.985 and reveals that the thickness of ribbon is inversely proportional to the wheel speed with the power of -1.231 which is in reasonable agreement with calculated and reported values. They found that as shorter and the melt drop has to a longer distance before solidification and the hardness of as spun ribbon decrease with increasing the wheel speed [7].

Adam L. Woodcraft predicted the thermal conductivity of Al-alloys in the cryogenic to room temperature based on a measurement of the thermal conductivity or electrical resistivity at single temperature [8]. Egami et al. proposed a correlation between the minimum solute concentrations that require for glass formation [9]. Wannaparhan used two common classes of numerical methods which are finite element method FEM and finite difference method FDM to study several important parameters such as the solid/liquid interface velocity and the cooling rate. All of these parameters can be correlated the final microstructure and properties of the casting. In addition, used numerical methods for the prediction of temperature distribution during solidification [10].

Zhang et al. applied thermo kinetic model to study the re-calescence characteristic in rapid solidification of copper. The effect of the heat transfer coefficient, the melt thickness and the nucleation temperature were investigated. Results showed that lower nucleation temperature and thinner melt lead to a longer re-calescence effect

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while larger heat transfer coefficient results in a weaker re-calescence effect. A dimensionless number was derived to measure the extent of re-calescence [11].

The empirical model proposed in this study is a useful prediction tool help to analysis the relationship between rapid solidification parameters (orifice diameter, nozzle-roll wheel gap, and melting temperature) and the thickness, hardness, and tensile strength of rapid solidified ribbons. It was applied without any materials, energy, and laborious time consuming, and without machining trials. The discovered empirical equations were feasible to make the prediction of mechanical properties. The constants and coefficients of these equations were calculated by multiple regression method using data-fit software.

The main advantages of data fit curve model is that it is easy to use and simple program which can be used as an aid for data visualization where no data are available and summarize the relationship among two or more variables. It is the process of constructing a curve or mathematical function that has the best fit to a series of data points; it is involved when ab exact fit to the data is required.

Experimental Work

Ribbon thickness is one of the most important factors that affect the heat transfer and the microstructure refining. Therefore, the effect of operation parameters that include orifice diameter, nozzle-roll wheel gap, and melting temperature on the ribbons thickness are studied. In this work, Al-Mg alloy type 5083 was used to product rapid solidified ribbons with very thin thickness in the range of micrometer. A series of rapid solidification process with single roll melt spinning technique were carried out to produce ribbons with different operation parameters [2-4]. The results were used to discover the empirical equations for prediction the mechanical properties of rapid solidified ribbons.

Discovered Empirical Equations

The indirect method represented by empirical equations is more particles for measurements. The multiple regression analysis method used to develop the empirical models to predict the ribbons thickness, grain size, hardness, yield strength, and tensile strength under difference conditions is curve-fitting treatment of data tools which is called data fit software or LAB Fit curve fitting software-V7.2.48-(1999-2011). Difference case study was used to discover the empirical equations for computing the mechanical properties for rapid solidified Al-Mg alloys type 5083.

Data fit for thickness

The discovered empirical equation that obtained in this work is shown in Equation (1). The correlation coefficient of this equation is equal to 0.93. The discovered equation was used to predict the thickness of ribbons TH depending on the melting temperature MT, and the distance between crucible nozzles and roll wheel surface G at constant orifice diameter OD equal to 2.5 mm. Therefore, the discovered empirical equation describes the behavior of rapid solidified ribbons thickness under the effect of melting temperature and distance between nozzle and roll wheel as shown in Figure 1 and the effect of distance on the ribbon thickness is shown in Figure 2. The constant values (A, B, C, and D) that used in the empirical equation of ribbon thickness are shown in Table 1 which was generated by the data fit program.

$$TH = \left(A*G^{(B+(C*MT))}\right) + \left(\frac{D}{MT}\right) \quad (1)$$

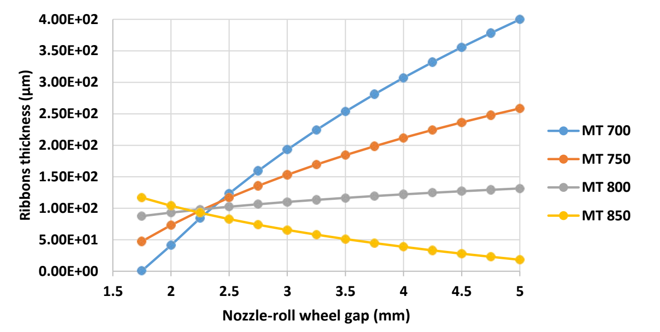

Figure 1: Effect of G and MT on the thickness of rapid solidified ribbons at constant OD equal to 2.5 mm.

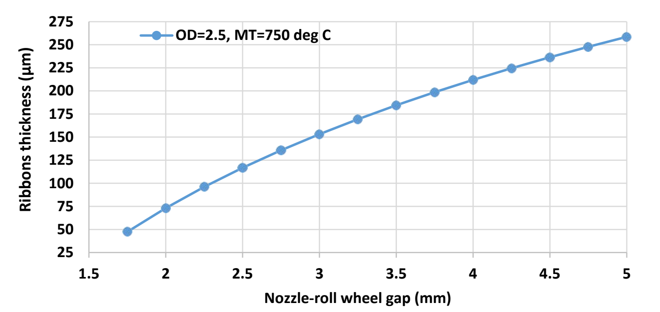

Figure 2: Effect of G on the thickness of rapid solidified ribbons at MT of 750°C and OD of 2.5 mm.

A	B	C	D
1885	1.21	-0.00149	-1455988

Table 1: Constant values.

A	B	C
-116.4	-0.135	95508

Table 2: Constant values.

Case No.	Variable Parameters		Constant Parameter
1	OD	G	MT 750
2	G	MT	OD 2.5

Table 3: Operation conditions.

Data fit for grain size

The discovered empirical equation for prediction the grain size GS of rapid solidified ribbons was discovered depending on the thickness of ribbons TH as shown in Equation (2). The constant values (A, B, and C) that used in the equation of ribbon grain size are shown in Table 2 which were generated by the data fit program. The regression value of this equation is 0.968.

$$GS = \frac{(A+TH)}{\left(B+\left(C*TH^2\right)\right)} \quad (2)$$

Data fit for hardness

The hardness of rapid solidified ribbons H computes using three parameters; one of them is constant and two are variants. The discovered empirical equations were obtained depending on the orifice diameter OD, nozzle-roll wheel gap G, and melting temperature MT as shown in Table 3. Equations 3 and 4 showed the empirical equations and their constant values (A1, B1, C1, A2, B2, C2, and D2) are shown in Table 4 which was generated by data fit program. Correlation coefficient of these equations is 0.97 and 0.89. The results from computations are shown in Figures 3-5 which demonstration the relationship between gap, ribbon thickness, and melting temperature. The better agreement between prediction and experimental data are shown.

$$H = (A1^*OD) + (B1^*G) + \left(\frac{C1}{OD^4}\right) \quad (3)$$

$$H = (A2+B2^*G)/(1+C2^*MT+D2^*MT^{\wedge}2) \quad (4)$$

Data fit for tensile strength

The hardness H that obtained by empirical equation can be used instead of the measured hardness value to compute the tensile strength TS value [12]. Equations (5, 6 and 7) were derived to get new empirical equation to predict the tensile strength of Al-Mg alloys ribbons without measuring the hardness of ribbons. The new discover empirical equation use to compute tensile strength depending on the orifice diameter (OD), and distance between nozzles and roll wheel (G) without doing any experimental work. Table 5 present the constant values (A, B, and C) of this equation which were generated by data fit program.

$$TS = K * \text{hardness} \quad (5)$$

A1	B1	C1	
15.44	-0.162	1799	
A2	B2	C2	D2
1.262	-0.0997	-0.0022	0.0000012

Table 4: Constant values.

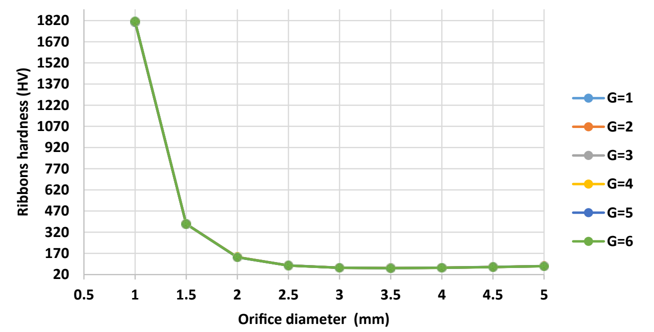

Figure 3: Effect of OD and G on the hardness of rapid solidified ribbons at constant MT equal to 750°C.

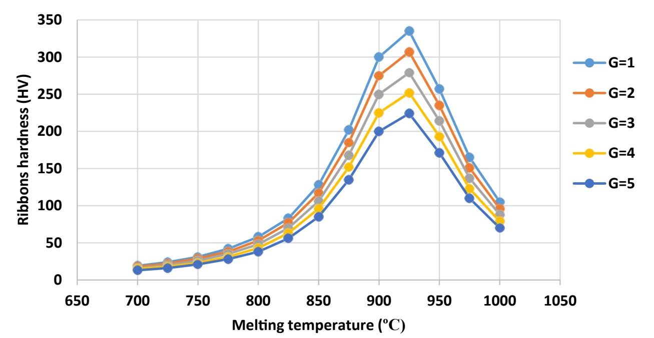

Figure 4: Effect of G and MT on the hardness of rapid solidified ribbons at constant OD equal to 2.5 mm.

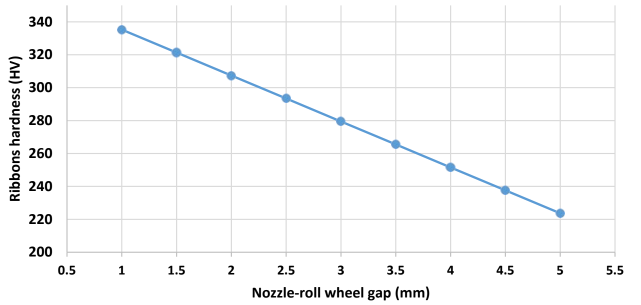

Figure 5: Effect of G on the hardness of rapid solidified ribbons at MT of 925°C and OD of 2.5 mm.

A	B	C
126316	55.4	-3.0994
A1	B1	C1
1884.68	1.21253	-0.001489
A2	B2	C2
-116.39	-0.1353	95508
A3	B3	C3
126315.5	55.43	-3.0994
D1		
-1455988		

Table 5: Constant values.

$$H = (A^*OD) + (B^*G) + \left(\frac{C}{OD^4}\right) \quad (6)$$

$$TS = K^*\left[(A*OD) + (B*G) + \left(\frac{C}{OD^4}\right)\right] \quad (7)$$

Data fit for yield strength

Yield strength YS of rapid solidified ribbons compute depending on the grain size of ribbons. Discovered empirical equation that use to predict yield strength is shown in Equations (8, and 9) and constant values (A, A1, A2, A3, B, C, B1, B2, B3, C, C1, C2, and C3) are presented in Table 5 which was generated by the data fit program. The relationship between yield strength and grain size is shown in Figure 6.

$$YS = A^*(\text{Ln}(GS+B))^{C} \quad (8)$$

$$YS = A3^*\left[\text{Ln}\left(\frac{A2+\left(\left(A1^*G^{(B1+(C1^*MT))}\right)+\left(\frac{D1}{MT}\right)\right)}{B2+\left(C2^*\left(\left(A1^*G^{(B1+(C1^*MT))}\right)+\left(\frac{D1}{MT}\right)\right)^2\right)}+B3\right)\right]^{C3} \quad (9)$$

Results and Discussion

The discovered empirical equations that obtained in this work can be used to predict the mechanical properties of rapid solidified ribbons types 5083 without doing any experimental work. It is depending on the major operation conditions of rapid solidification process include orifice diameter, nozzle-roll wheel gap, and melting temperature. A predict mechanical properties include ribbons thickness, hardness, and tensile strength. The result curve showed that when the distance between crucible nozzle and roll wheel surface increased the ribbon thickness increased which agree with the experimental work. This relationship depends on the melting temperature. For instant, when the melting temperature equal to 700, 750, and 800°C, the above relation is correct. But, when the melting temperature increase more than 800°C, ribbons

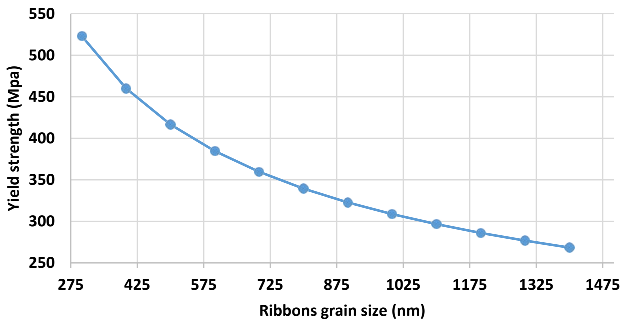

Figure 6: Effect of G on the yield strength of rapid solidified ribbons for 5083.

thickness decrease with increasing the distance between nozzle and roll wheel as shown in Figures 1 and 2. The dependence of the ribbon dimensions on single roll melt spinning parameters has been presented in terms of mathematical expressions. Due to increasing the thickness of ribbons with increasing the distance between nozzle and roll, the hardness of ribbon was decreased which agree with the relationship that obtained by empirical modelling as shown in Figure 5. Additionally, Figure 4 showed that the hardness of ribbons increases with increasing the melting temperature up to 925°C, then decrease with increasing the melting temperature. On the other hand, the hardness increase with increasing the distance between nozzle and roll gap especially when the melting temperature increased. From Figure 3 can be indicated that the hardness of ribbons decreased with increasing the orifice diameter. This relationship is constant for all distance between nozzle and roll. There is inverse proportional relationship between yield strength and orifice diameter as shown in Figure 6. When the grain size increase, the yield strength decreased. However, hardness is directly proportional to tensile strength. With the hardness increase, the tensile strength increased too.

The rapid solidification technique was found be effective process for refining structural particles in 5083 alloy, where highly refined intermetallic components as well as grain size were found to be beneficial to the modification of mechanical properties.

Conclusions

It can be concluded that the hardness, yield strength and tensile strength of 5083 Al-alloy ribbons increased by rapid solidification process. There is a good agreement between experimental results and empirical results, where the correlation reached to 0.99. Empirical modelling and equation are economical and useful for predicting of mechanical properties for rapidly solidified alloys which forming by single roll melt spinning process. The maximum ribbon hardness was obtained at melting temperature equal to 925 degrees centigrade with orifice diameter of 2.5 mm and gap between orifice nozzle and roll surface equal to 1 mm. The major factors that influence the mechanical properties of rapidly solidified ribbons are the shape and grain size of ribbons, because hardness and yield strength of rapidly solidified ribbons were increased with degreased the ribbon grain size and ribbons thickness.

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