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Theoretical Analysis of Liquid Aluminum Flow in Aluminum Casting Processes

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Taiwo Alare[1]* and Feranmi J Adeloye[2]

[1]*Department of Mechanical Engineering, Stony Brook University, NY*

[2]*Department of Civil Engineering, Ladoke Akintola University of Technology, Ogbomosho, Nigeria*

***Corresponding Author:** Taiwo Alare, Department of Mechanical Engineering, Stony Brook University, NY.

Abstract

Aluminum casting is a manufacturing process that has been around for some time. This method has been used in making many aluminum products used as parts of aircraft, automobiles, turbines, and structures like bridges. Every cast product is expected to be of the desired and required strength so it will not fail on application. It is good to predetermine the strength of aluminum cast accurately at the design stage before casting. Therefore, we developed a model that can predict the aluminum cast's strength and other mechanical properties by studying the flow profile of liquid aluminum flowing through the mold.

Keywords: Strength of cast; Aluminum casting; Fluid mechanics; Flow properties

Introduction

Metal casting is a metal manufacturing process such that a liquid metal is usually poured into a casting mold that contains a hollow cavity of the desired shape, which is then allowed to solidify [1]. Metal casting is an old technology which has been around for about 7000years and it is applied in both manufacturing and artwork [2]. Metal casting as the following processes: Mold cavity making, liquification of metal, injection of liquid molten metal into the mold cavity, solidification, product is taken out of the mold cavity, product finishing [3]. The solidified metal is known as a casting, which is ejected or broken out of the mold to complete the process, it is then trimmed and sharpened to the required shape and dimension [1]. metal casting can be employed when manufacturing a product with a complex shape geometry such as such as internal combustion of engine, combustion chamber casing of gas turbine. It can also be employed when working with materials of low ductility such as high carbon steel [1]. It can also be used when specified geometry is required such as aircraft door [4]. The type of metal casting is sand, die, investment, continuous casting [1]. Metal casting processes are relatively inexpensive and allow complex shape metal manufacturing. The most common type of casting is sand casting, [4] but dimensional in accuracy and rough surface finish of the castings made by sand casting processes are a limitation to this technique [3]. Also, formation of slag during metal casting processes also contributed but to wastage and it is another limitation of metal casting processes. The study of the flow of the molten metal in the mold cavity can solve this limitation of metal casting.

Aluminum is a metallic element which is solid in its natural state and the second most abundant metallic element on Earth [5]. this makes it one of the cheapest metals on Earth. It was discovered in the year 1825 by a Denmark scientist Mr. Hans, using chemical process [6]. Aluminum has a density of 2.7 g/cm^3. Aluminum is a good conductor of heat and electricity and has electronic configuration of $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^1$. The chemistry of aluminum shows that aluminum of 13proton, 14neutron, and 13electron and only have one valence electron [5]. This classified aluminum to be a group one element and makes it to be very reactive. Like some other metals, Aluminum can also be casted, and this casting processes is known as aluminum casting [6]. it was developed in 1875 using sand casting [6]. In aluminum casting, aluminum is melted into a liquid phase with a furnace, and the liquid aluminum is injected into the casting mold cavity via the mold runner. It is allowed to solidify and then assume the shape of the mold. The fineness of the cast depends on the mechanics of the liquid aluminum flow in the mold cavity and the energy (thermal) interaction. Aluminum and aluminum alloy casting is used in aircraft manufacturing and gas turbine manufacturing. This makes this study significant.

The paper assumes that there is no change in liquid aluminum temperature at the entry point, so the liquid aluminum temperature is the melting point temperature of aluminum which is 660°C [7]. The research aims to study the flow characteristics of liquid aluminum to determine its effect on the strength contribution (the material characteristics) of the cast using Navier-stoke moment and energy equation to determine the velocity profile and hydrodynamics entrance length.

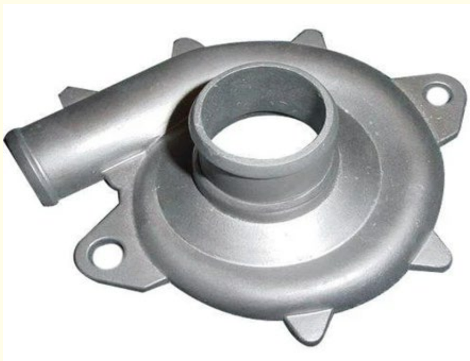

Figure 1.0: Aluminum cast centrifugal pump casing.

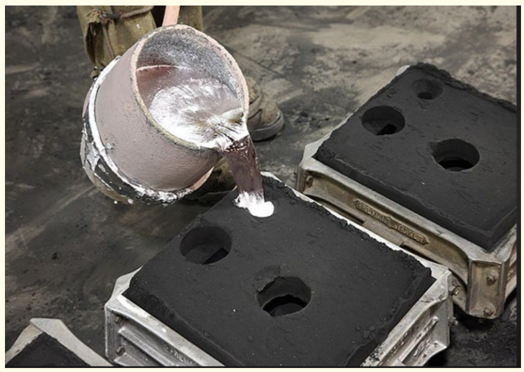

Figure 1.1: Aluminum casting process.

Methods

The liquid aluminum flow in the mold is assumed to be unidirectional laminar/viscous flow. The flow is at a steady state with no slip wall boundary condition. Navier-Stoke momentum equation is used to model the flow.

$$\alpha Re\left(\frac{\partial U_x}{\partial t}+U_x\frac{\partial U_x}{\partial x}+U_z\frac{\partial U_x}{\partial z}\right)=-\frac{dp}{dx}+\alpha^2\left(\frac{\partial^2 U_x}{\partial x^2}+\frac{\partial^2 U_x}{\partial z^2}\right)$$

$$\lim_{\alpha\to 0}\left(-\frac{dp}{dx}+\frac{\partial^2 U_x}{\partial z^2}=0\right)\to$$

$$U_x=-\frac{1}{2\mu}\frac{dp}{dx}\left[zR-z^2+U\left(1-\frac{z}{R}\right)\right]\to Slit\ flow\ [1]$$

Where U_x is the velocity of the flow, Reynolds number Re = $^{\rho VD}/_{\mu}$, α = f (ρ, V, D, μ) and $dp/dx \to \nabla p$ is the pressure gradient. r is a height function of x, $R(x)$ and μ is dynamic viscosity. The velocity of Aluminum flowing through the runner ingate to the mold cavity is modelled to no slip [8], the upper and low mold is taken as a no slip wall and boundary condition is given below. The flow is assumed to be fully developed [8].

$u_r = U = 0$
$u_x = 0$ at $r = 0$
$u_x = U_x$ at $r = R/2 = \delta$

The cast cavity is assumed to be flat, and the radius is uniform although the mold geometry i.e., $r(x)_{x=0} = r(x)_{x=x} = R$. A second-degree polynomial velocity profile is used [8].

$$\frac{u_x}{U_x} = \alpha_0 + \alpha_1 r + \alpha_2 r^2$$

With the additional boundary of $dux/dr = 0$ at $r = \delta$ we can determine the α - *coefficients*.

$$\alpha_0 = 0,\ \alpha_1 = {}^2/_{\delta},\ \ \alpha_2 = -{}^1/_{\delta^2}$$

Similarity function $\zeta,\ \frac{u_x}{U_x} = \frac{r}{\delta} = f\zeta\ \ \zeta = \frac{r}{\delta}$

$$\frac{u_r}{U_x} = 2\zeta - \zeta^2$$

The shear stress of casting is determined assumed to be the strength of the cast material after solidification.

$$\tau = \mu \frac{du_x}{dr|r=0}\ ,\ \ dr = \delta d\zeta,\quad \frac{du_x}{dr} = \frac{1}{\delta}(2 - 2\zeta)U_x|_{\zeta=0} = \frac{2U_x}{\delta}$$

$$\tau = \frac{2\mu U_x}{\delta}$$

The viscosity of liquid aluminum is given as [9].

$$\log_{10}\left(\frac{ℷ}{ℷ^{\circ}}\right) = -a_1 + \frac{a_2}{T} \qquad 933 \le T(K) \le 1270$$

$$ℷ^0 = 1mPa.s,\ a_1 = 0.7324,\ \ a_2 = 809.49K\ [10]$$

At melting temperature T= 933K.

$$\log_{10}\mu = -0.7324 + \frac{803.49}{933},\ \log_{1o}\mu = 0.12878971061$$

$$\mu = 1.3452mPa.s$$

$$\tau = \frac{2\times\mu U_x}{\delta}$$

$$\delta = \frac{R}{2},\qquad U_x = \frac{\dot{m}}{\rho A} = -\frac{1}{2\mu}\frac{dp}{dx}\left[zR - z^2 + U\left(1 - \frac{z}{R}\right)\right]$$

$$\text{at} z = \delta = \frac{R}{2} = r, U = 0\ then\ U_x = \frac{\dot{m}}{\rho A} = -\frac{1}{2\mu}r^2\frac{dp}{dx}$$

The pressure gradient is determined by LaPlace’s law.

$$\Delta p = -\frac{2\gamma}{r_{in}}, l_c = \sqrt{\frac{\gamma}{\rho g}},\ \frac{dp}{dx} \approx \frac{\Delta p}{l_c} = \frac{-2\sqrt{\gamma\rho g}}{r_{in}}$$

$$U_x = \frac{\dot{m}}{\rho A} = -\frac{1}{2\mu}r^2\frac{-2\sqrt{\gamma\rho g}}{r_{in}}$$

Δp is pressure gradient,
γ is surface tension, r_{in} is the enterance or runner radius, r is the mold cavity radius.

$$\dot{m} = \frac{\rho A r^2\sqrt{\gamma\rho g}}{\mu r_{in}}$$

$\dot{m}$ is the mass flowrate, A is the mold cavity area which is a function of diameter $A(R)$, ρ is the mass density of aluminum $\rho = 2.7 \times \frac{10^3 Kg}{m^3}$ [11]. The surface tension γ of aluminum at melting point is given as 875 mN m^{-1} [10]. The volume of the mold cavity is given by $v = Ar$ and the viscosity $\mu = 1.3452 mPa.s.$ g is gravitational acceleration $g = 9.8 m^2 s^{-1}$, $D = \frac{r}{r_{in}}$ The relationship between mass flowrate of aluminum and the volume of the mold cavity is given by.

$\dot{m}$ =305336.7vD Kgs^{-1}

The flowrate Q is given by $Q = 0.32523v\ m^3\ s^{-1}$.

The maximum shear stress at δ = R/2 = r is given by,

$$\tau = 304.32D\ N/m^2$$

Conclusion

The paper shows that the shear stress and strength of aluminum cast can be predetermined before casting.

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