“IMPROVEMENT IN TRIBOLOGICAL PROPERTIES BY IMPROVING GEOMETRY OF REINFORCEMENT PARTICLES”

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Abstract
The volume fraction of the heavier Titanium Di-boride particles is controlled by inertial forces upon centrifugal force processing the semisolid composite. Titanium Di-boride particles are modeled as tetrahedron particles subject to a drag force in a Stoke flow. The equation of motion for the particles under the applied centrifugal forces is solved mathematically assuming a Gaussian diameter size distribution with a spatial uniform random distribution of particles in the sample. The effect of the geometry of the particles is also important. It is observed that the Penetration capability of reinforcement particles is dependent on the shape and the geometry of the particles. Drag force is kept at the minimum by adopting tetrahedron shape particles. It is possible to understand and control the experimental conditions to obtain an appropriate functionally-graded aluminum matrix by centrifugal casting for high wear resistance applications.

Keywords: Functionally graded matrix, Titanium diborides , Tetrahedron particles

1. Introduction

Aluminum and its alloys posses advantages such as low cost, high strength to weight ratio, low specific weight and hence find wide applications in automotive, aviation and space industries. However the main limitations of their wider application for the commercial purpose is lack of mechanical strength, surface hardness and wear resistance together with low chemical and thermal stability. The use of aluminum for light weight machine parts and car components has recently increased although non metallic materials such as resin are also used for this purpose. Aluminum have advantages over non metallic materials such as corrosion resistance, light weight and has good thermal conductivity. However the wear, hardness and seize resistance of aluminum is lower than that of other metals such as steel and hence there is a limit on application as sliding parts. Surface modification and coating are widely used to improve tribological properties of metallic materials, but the added surface treatment increases the manufacturing costs. On the other hand, centrifugal casting appears to be an effective method to prepare the metal matrix composite called FGMs whose composition vary over geometrical length. Thus Functionally graded materials (FGMs) are spatial composites that display discrete or continously varying composition as in [1] over a geometrical length.The segregation of particles during centrifugal casting of metal matrix composite occurs due to centrifugal force, either at the inner or outer periphery of the casting, depending on the relatives densities of the particles and the melt, resulting in particles reinforced functionally gradient composites. The extent of segregation depends on various process parameters

The parameters that influence solidification structures as given in [2] includes solidification time, the mold rotation velocity, the cast geometry, density difference between matrix and reinforced particles, the mold preheating temperature, the pouring temperature of the molten metal and the alloy composition etc. If the density of the particles is higher than that of molten matrix, the particles migrate towards outer radial direction. The reinforcement particles move in the radial direction due to its higher density than liquid alunimium.

In some previous work,a hollow cylinder rotating vertically around the central axis is considered as in [3].Because of this configuration, they had to consider the effect of gravity. In this work the effect of gravity in the movement of particles is neglected because the radial acceleration is much higher than the gravity acceleration. In the present work the molten matrix, with the reinforcement particles, (TiB2) is put into a cantilever type cylindrical mold and then exposed to a centrifugal action with its central axis along the radial direction. The particle size distribution plays an important role in controlling the mechanical properties of the sample. A mathematical model for the motion of the particles is formulated, and the model divided into different cases, each one corresponding to different assumptions up to the more general case that relax the assumptions made. This will help us in noticing how each parameter affects the results. Solidification plays an important role in the final volume fraction of particles .Experimental work is carried out to check whether the mathematical results are in good prediction or not. This method gives us an unique approach to improve surface hardness and wear resistance of the composites.

2. Mathematical Model

A schematic diagram of the centrifugal casting sample is shown in Fig.01. Consider a tetrahedron shape solid particles in an aluminum matrix. Particles are assumed uniformly distributed in the liquid aluminum matrix. The sample is rotated at a constant centrifugal speed ω.Tetrahedron shaped Titanium Diboride particles have higher density than the density of the liquid Aluminum matrix.

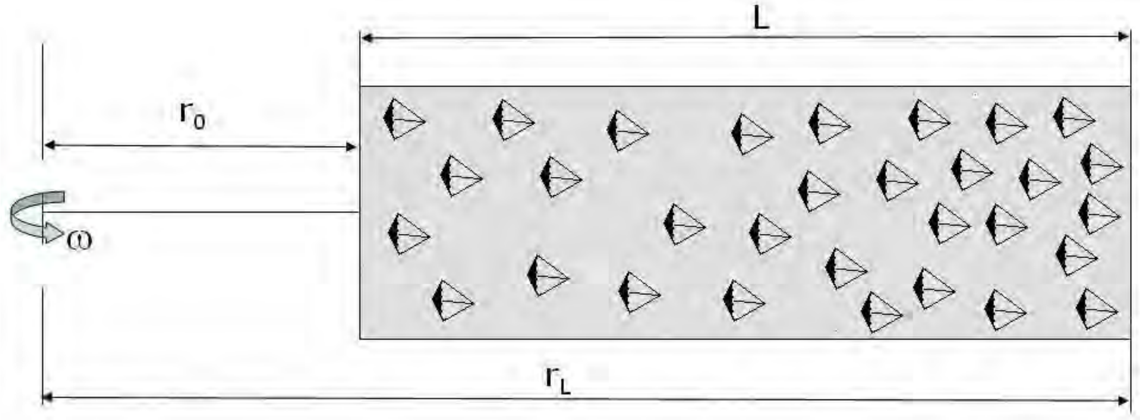

Fig.01. Centrifugal casting Systamatic diagram

Let

r'=dimensionless radial coordinate
t =time
a=edge length of the particle
m_p= mass of the particle
r=radial position of particle
τ =dimensionless time
θ =angular velocity of the particle
ω=angular velocity of the sample
ρ =density of the aluminum matrix
ρ_P =density of particles
μ =dynamic viscosity
μ_0 =reference dynamic viscosity
H=heat transfer coefficient
h = height of right tetrahedron
c_p = specific heat

N= Number of particles
T =Temperature
T_i, T_a =initial temperature of the sample and ambient temperature, respectively
A=area of particle
V= volume of particle
r_o =distance of cylinder side to the axis of rotation.
r_L = distance of cylinder side further away from the axis of rotation.

The equation of motion for the particles in a rotational stoke flow is,[4]

$$m_p[(\ddot{r} - r\dot{\theta}^2)e_r + (r\ddot{\theta} + 2\dot{r}\dot{\theta})e_\theta] = -6\pi\mu a[\dot{r}e_r + r(\dot{\theta} - \omega)e_\theta] \tag{1}$$

Thus, the two equations of motion in radial and circumferential directions are given equation (2) & (3)

$$m_p\ddot{r} = -6\pi\mu\, a\, \dot{r} + m_p r\dot{\theta}^2 \tag{2}$$

$$m_p r\ddot{\theta} = -6\pi\mu\, a r\, (\dot{\theta} - \omega) - 2m_p\dot{r}\dot{\theta} \tag{3}$$

Subject to the initial conditions: *at* $t = 0$, $r = r_0$; $\dot{r} = 0$; $\theta = 0$; $\dot{\theta} = \omega$

2.1Dimensionless Form of the Equations of Motion

2.1.1 Radial direction:

Let, m_p = mass of the particle and assuming particle has **tetrahedron shape profile**

$$m_p = \rho_p V = \rho_p \times \frac{1}{3} \times A_o \times h \qquad (A_o = \frac{\sqrt{3}}{4} \times a^2 \;, h = \frac{\sqrt{6}}{3} \times a)$$

$$= \rho_p \times \frac{\sqrt{2}}{12} \times a^3, \textit{where } a = \textit{edge length of regular tetrahedron}$$

$$\frac{d^2r}{dt^2} = \frac{-72\ \pi\mu}{\sqrt{2}\, a^2\ \rho_p} \times \frac{dr}{dt} + r\,\dot{\theta}^2$$

Defining the dimensionless parameters: $\tau = \frac{\mu_o t}{\rho a^2}$, $r' = \frac{r}{r_o}$, and $\mu' = \frac{\mu(T)}{\mu_o}$. and doing a change of variable ,the dimensionless equation is obtained,

$$\frac{d^2r'}{d\tau^2} = -\frac{72}{\sqrt{2}} \times \pi \times \frac{\rho}{\rho_p} \times \mu' \times \frac{dr'}{d\tau} + r'\left(\frac{d\theta}{d\tau}\right)^2 \tag{4}$$

The dimensionless forms of the initial conditions are:

$$\text{at} \quad \tau = 0 \quad r' = 1 \ ; \ \frac{dr'}{d\tau} = 0 \tag{5}$$

2.1.2 Circumferential direction :

In the same way, the dimensionless form of equation (4) in the circumferential direction is:

$$r'\frac{d^2\theta}{dx^2} = -\frac{72}{\sqrt{2}} \times \pi \times \frac{\rho}{\rho_p} \times \mu' r'\left(\frac{d\theta}{d\tau} - \frac{\rho\omega a^2}{\mu_0}\right) - 2\frac{dr'}{d\tau}\frac{d\theta}{d\tau} \tag{6}$$

With the following dimensionless form of the initial conditions:

At $\tau = 0\;;\;\theta = 0;\frac{d\theta}{d\tau} = \frac{\rho\omega a^2}{\mu_0}$

From equations (4) and (6), three dimensionless parameters are identified:

$$\rho' = \frac{\rho}{\rho_p} \qquad \mathrm{Re}_a = \frac{\rho\omega a^2}{\mu_0}$$

The last parameter takes into account of the dependency of temperature with viscosity. Due to high thermal conductivity of the aluminum and the small convection coefficient, a small Biot number can be assumed and the sample is treated as a lumped capacitance system. For a lumped system, the temperature of the sample will be only function of the time and can be calculated by knowing the thermal time constant initial temperature, ambient temperature as refered in [5]. By knowing the variation of the viscosity with the temperature ,the viscosity as the a function of time can be evaluated

$$\mu = f[T(t)] = f_1(t)$$

The convection coefficient can be estimated from a Nusselt correlation.

3.Analytical Solution:

Parametric study is carried out to understand importance of the dimensionless parameter Re_a and $\frac{\rho}{\rho_p}$.Also, the effect of temperature for constant viscosity is analyzed .Neglecting the differences between $\dot{\theta}$ and ω (i.e $\dot{\theta} = \omega$) the equation of motion (4) becomes:

$$\frac{d^2 r_i}{d\tau^2} = -\frac{72}{\sqrt{2}} \times \pi \times \frac{\rho}{\rho_p} \times \frac{dr_i}{d\tau} + \left\{\frac{\rho\omega a_i^2}{\mu_o}\right\}^2 r_i$$

Here $\frac{d\theta}{d\tau} = \frac{\rho a_i^2 \omega}{\mu_0} =$ constant , a_i is the radius of the particle i and r_i is the its radial position.

The initial conditions are ,at $\tau = 0$; $r = 1 + \frac{r_L - r_0}{r_0} \times \mathrm{rand}(N,1)$; $\frac{dr}{d\tau} = 0$,

Where N is the number of particles.

N equations are solved, one for each particle. Since the flow is laminar, each particle follows its own path line without colliding with other particles. So, under these assumptions, the following second order linear differential equation is solved:

$$\frac{d^2 r_i}{d\tau^2} + \frac{72}{\sqrt{2}} \times \pi \frac{\rho}{\rho_0} \frac{dr_i}{d\tau} - \left(\frac{\rho a^2 \omega}{\mu_0}\right)^2 r_i = 0$$

Here, a = 1 , $b = \frac{72}{\sqrt{2}} \times \pi \frac{\rho}{\rho_p}$, $c^2 = \left(\frac{\rho a^2 \omega}{\mu_0}\right)^2$

The roots of the characteristic equation are:

$$\alpha_1 = \frac{-b}{2}(1 + \sqrt{1 + 4(c/b)^2} \qquad ; \qquad \alpha_2 = \frac{-b}{2}(1 - \sqrt{1 + 4(c/b)^2}$$

And the general solution is:

$$r(\tau) = A_1 e^{\alpha_1 \tau} + A_2 e^{\alpha_2 \tau}$$

Applying the initial conditions;

At $\tau = 0$; $\quad r_{init} = 1 + \frac{r_L - r_0}{r_0} \times \mathrm{rand}(N,1);$ $\quad \frac{dr}{d\tau} = 0$

The analytical solution is obtained as,

$$\frac{r(\tau)}{r_{init}} = \left(\frac{1+\sqrt{1+4(c/b)^2}}{2\sqrt{1+4(c/b)^2}}\right)e^{\left[\frac{-b}{2}\left(1-\sqrt{1+4(c/b)^2}\right)\tau\right]} - \left(\frac{1-\sqrt{1+4(c/b)^2}}{2\sqrt{1+4(c/b)^2}}\right)e^{\left[\frac{-b}{2}\left(1+\sqrt{1+4(c/b)^2}\right)\tau\right]}$$

Where $b = \frac{72}{\sqrt{2}} \times \pi \frac{\rho}{\rho_p}$ And $\frac{c}{b} = \frac{\sqrt{2}}{72} \times \frac{1}{\pi} \frac{\rho_p a^2 \omega}{\mu_0}$

Substituing the values of b.c / b in analytical solution, the radial position of particles can be obtained which gives the idea of the effect of various parameters on casting and particle distribution.

4.Experimentation

Experimentation is carried out to prepare the samples on the cantilever type centrifugal casting machine. The die is rotated with help of belt and pulley arrangement as shown Fig.02 The walls of a cylindrical mold are first coated with a refractory ceramic coating, which involves a few steps .(application, rotation, drying, and baking). Once prepared and secured, the mold is rotated about its axis at high speeds 300rpm to -3000 rpm. Molten metal is poured directly into the rotating mould, without the use of runners or a gating system. The centrifugal force drives the material towards the mould walls as the mould fills. With all of the molten metal in the mould, the mould remains spinning as the metal cools. Cooling begins quickly at the mold walls and proceeds inwards. After the casting has cooled and solidified, the rotation is stopped and the casting can be removed. Fig.03 shows the special purpose die & Fig 04 shows ring of samples pins.

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Fig 02.Experimental Set up

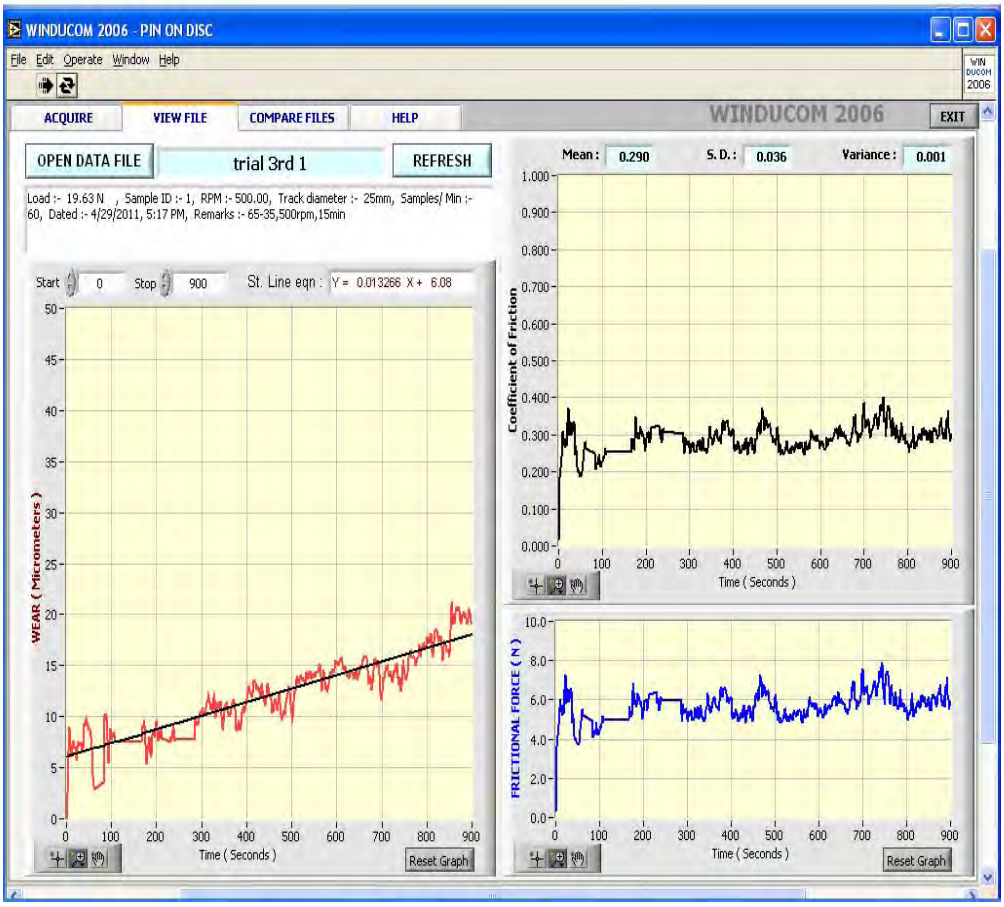
Fig 03 Special Purpose Die

Fig 04 Ring of Sample Pins

5. Results and Discussions

- Pin Diameter : 10 mm Track Diameter : 25 mm Test Duration : 15 min.
- Speed: 500 rpm and 800 rpm

5.1 Composition: Al- 97.50% , TiB_2- 2.5%, Testing Speed N = 500 rpm



trial 3rd 1

Load :- 19.63 N , Sample ID :- 1, RPM :- 500.00, Track diameter :- 25mm, Samples/ Min :- 60, Dated :- 4/29/2011, 5:17 PM, Remarks :- 65-35,500rpm,15min

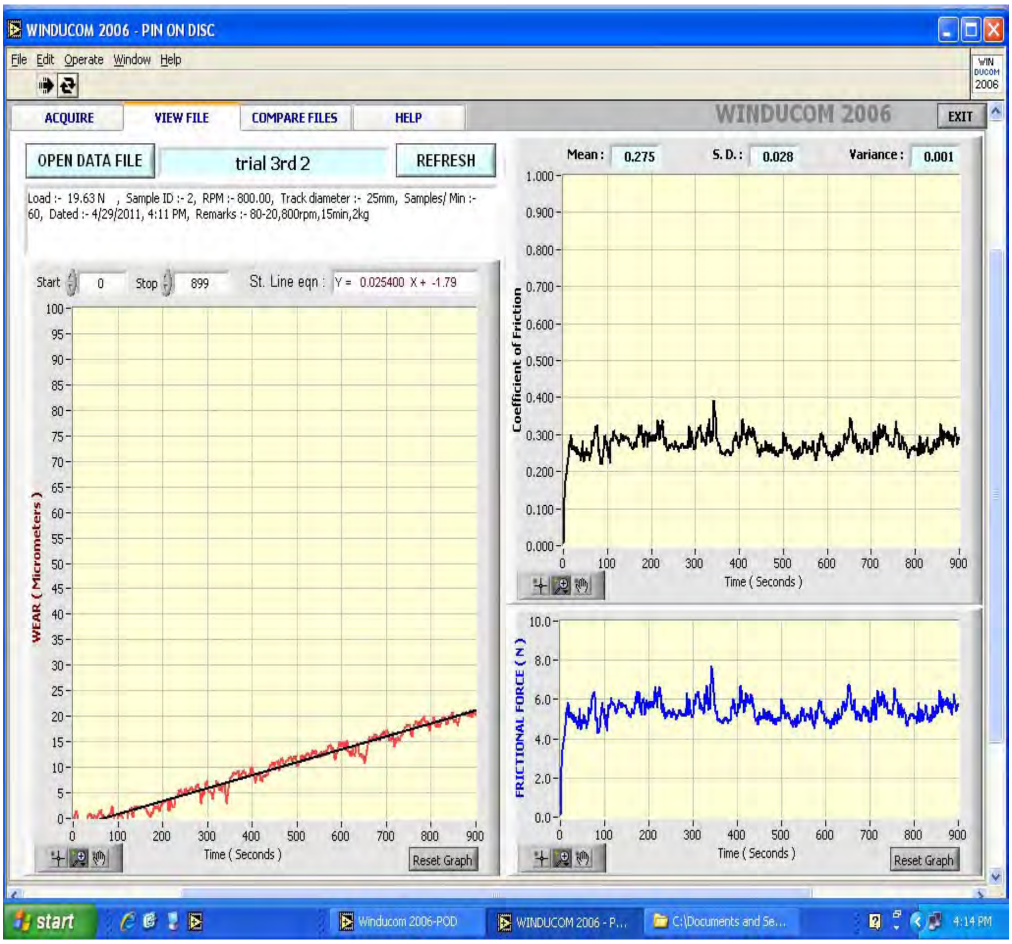
Start 0 Stop 900 St. Line eqn : Y = 0.013266 X + 6.08

Mean : 0.290 S. D. : 0.036 Variance : 0.001

Fig . 05. Wear,Co-efficient of friction & Frictional Force VS Time Al- 97.50% TiB_2- 2.5%

- From the Fig 05 , it is seen that as the time increases wear increases, however the frictional force and co-efficient of friction increase rapidly and then fluctuate about a certain value.
- The wear range varies from 0-20 µm.**At 900 sec wear is 20 µm**

5. 2 Composition: Al- 97.50%,TiB_2- 2.5% ,Testing speed N = 800 rpm



trial 3rd 2

Load :- 19.63 N , Sample ID :- 2, RPM :- 800.00, Track diameter :- 25mm, Samples/ Min :- 60, Dated :- 4/29/2011, 4:11 PM, Remarks :- 80-20,800rpm,15min,2kg

Start 0 Stop 899 St. Line eqn : Y = 0.025400 X + -1.79

Mean : 0.275 S. D. : 0.028 Variance : 0.001

Fig. 06. Wear, Co-efficient of friction & Frictional Force VS Time Al- 97.50%,TiB_2- 2.5%

- From Fig 06, it is seen that as the time increases wear increases; however the frictional force and co-efficient of friction increase rapidly and then fluctuate about a certain value.
- The wear range varies from 0-20 µm.**At 900 wear is 21 µm**

6. Conclusions

Particles with a spatial uniform random distribution and a Gaussian diameter size distribution are assumed as an initial condition of the casting process. Substituting the values of parameters in analytical solution, the radial position of particles are obtained which gives the idea of the effect of various parameters on casting and particle distribution. The two important control parameters of the centrifugal casting process are the rotation speed and the time of centrifugation. The mathematical model developed to predict the dispersion of reinforcement particles in metal matrix composite to be produced by centrifugal casting method is useful for the researchers to predict the wear and the suitability of Materials for number of applications. It is found that the effect of the geometry of the particles is important. As penetration capability of reinforcement particles is dependent on the shape and the geometry of the particles. By adopting tetrahedron shape particles the drag force is kept at the minimum.

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