Manufacturing Letters 13 (2017) 21–24

Contents lists available at ScienceDirect

Manufacturing Letters

journal homepage: www.elsevier.com/locate/mfglet

Letters

Using Taylor vortices to create a film of nanoparticles for dip-coating

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A R T I C L E I N F O

Article history:
Received 9 November 2016
Received in revised form 23 May 2017
Accepted 25 May 2017
Available online 27 May 2017

Keywords:
Nanoparticles
Dip-coating
Taylor vortices
Nanoparticle coating

A B S T R A C T

Taylor Couette flow is of importance for specific engineering applications like high-speed journal bearings. At the same time, nanoparticles thin film coating has attracted researchers to modify the surface properties of different substrates. Here, a novel and simple coating technology based on Taylor Couette flow is proposed, for coating a wide range of materials.

Thin films of nanoparticles were created on the surface of a nanoparticle dispersion by Taylor vortex flow, allowing subsequent transfer of the films by dip-coating on various materials. Scaling laws were derived for the coating setup allowing its application for a wide range of sample sizes.

1. Introduction

First experimental and theoretical investigations on the stability of a viscous flow between two rotating cylinders, known as Taylor Couette flow, were conducted by Taylor [1]. Since then, it has been a model for hydrodynamic stability and origins of turbulence in fluid physics and other fields of engineering [1–3]. Especially the concept of an eccentric rotating cylinder within a stationary cylinder is of great importance for specific engineering applications like wellbore drilling and high-speed journal bearings [4]. In the latter, damaging effects of impurities contained in oil can be considerably reduced when they are removed from the friction contact area by increasing axial oil flow [5]. The rotational speeds, geometry of the cylinders and the viscosity of the fluid in the annulus are factors that influence the stability of the flow. These parameters define the dimensionless Taylor number which characterizes the state of Taylor Couette flow. The first state is the laminar, stable and axisymmetric circular Couette flow. When instability sets in above critical conditions (characterized by the critical Taylor number) the flow will experience super laminar flow in the form of Taylor vortex flow and subsequently lead to turbulent flow. This Taylor vortex flow is due to centrifugal forces, causing the development of a secondary circulatory flow pattern in the form of many toroidal vortices spaced periodically in the axial direction [1–3,6].

At the same time, nanoparticles thin film coating has attracted researchers to modify the surface properties of different substrates [7,8]. Different processes have been developed to create thin films of nanoparticles for novel applications in various areas such as photonics, catalysis, sensors, and biomaterials [7]. Although different methods provide a way to create thin films of nanoparticles on surfaces, they are rather complicated and in most cases organic solvents are required [9–12].

This letter reports a method to create a thin film of nanoparticles on the surface of an aqueous solution [13]. In this study, it is showed that the driving force of the process is the Taylor vortex flow, which can be used to transport dispersed nanoparticles from the bulk solution to the surface. The formed film can subsequently be transferred by dip-coating to a wide variety of substrates and therefore be used as a coating technology. It is further demonstrated that the process can be scaled allowing its application for a wide range of sample sizes.

2. Materials and methods

The experimental setup consists of (Fig. 1):

- Recipient with colloidal solution of nanoparticles (100 ml glass beaker)
- Spindle with mixing rod (Teflon, diameter = 19.16 mm)
- Actuated z-stage

First, a thin film of nanoparticles on the top surface of the dispersion of nanoparticles in deionized water (DI) is created by the eccentric rotating mixing rod in the glass beaker inducing a reversed Taylor flow (Fig. 2b) on the surface and an axial flow in the bulk of the solution [1,6,14]. Particles are delivered upwards

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http://dx.doi.org/10.1016/j.mfglet.2017.05.004

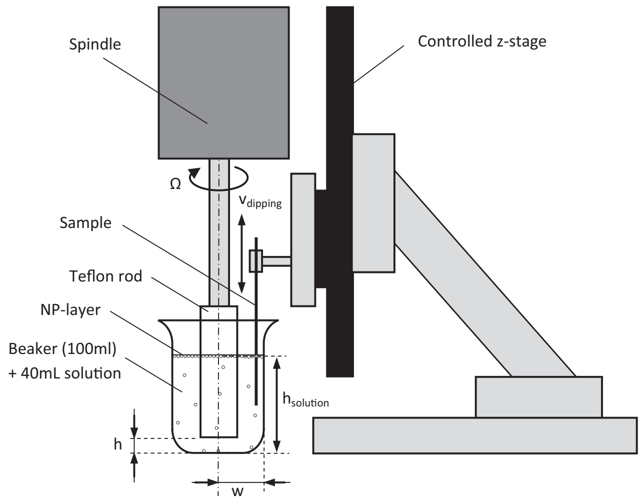

Fig. 1. Dip-coating set-up (front side) in laboratory with dipping control equipment. The rotating mixing rod (Teflon) is placed at height *h* from the bottom of the beaker and distance *w* from the side of the beaker.

and a shiny layer of nanoparticles on top of the solution is eventually formed.

Secondly, the film is transferred to a substrate by dip-coating [15]. Varying the number of dipping (n) allows controlling the coating thickness (t) if sufficient drying time is kept in between (typically 1 h). A linear correlation between n and t was found, which was evaluated by using a stainless steel substrate and nickel nanoparticles. Each dipping resulted in an increase of 1 μm of the coating thickness.

A subsequent heat treatment (1 h @ 100 °C followed by 3 h @ 400 °C with a temperature rate of 40 °C/min) was applied to increase the coating adherence on the substrate.

Spherical nickel nanoparticles (SkySpring Nanomaterials Inc., art.# 9221XH) with diameter distribution of 60 nm–80 nm were employed. The coated substrates were stainless steel and aluminum rectangles (25 mm × 10 mm × 1 mm).

3. Theory

Flow between two rotating cylinders is characterized by the dimensionless Taylor number T. Increasing T exhibits multiple

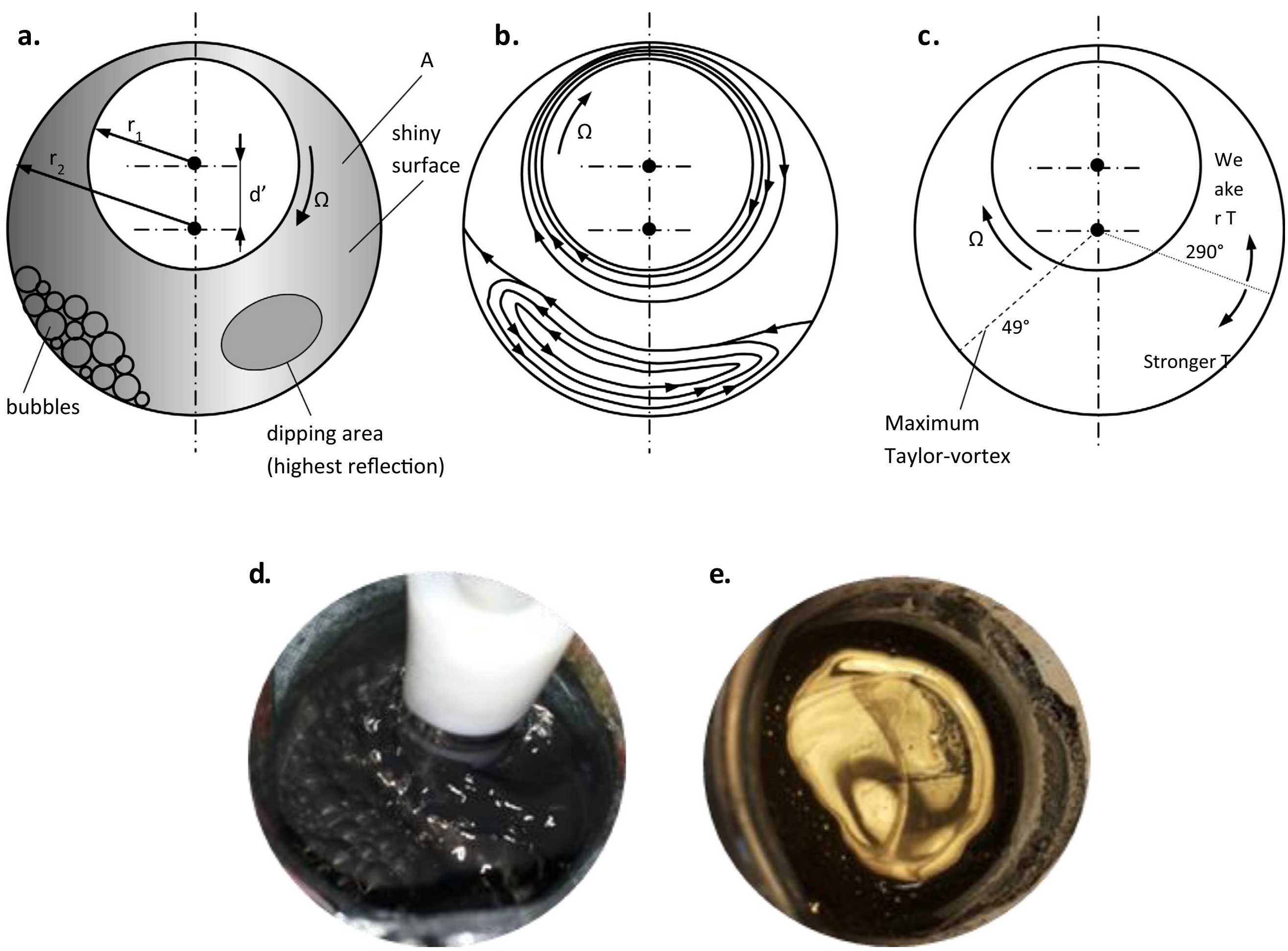

Fig. 2. **a.** Dip-coating set-up (top-side) with eccentric cylinder flow, highlighting the bubble formation area together with the dipping area. The surface (A) is shiny due to the formed layer of nano-particles on the solution. **b.** Eccentric Taylor-Couette flow pattern [17]. **c.** Schematic of Taylor vortex flow with location of maximum Taylor-vortex strength 49° downstream of the point of maximum gap. Separation of the flow starts around 290° downstream [1–3,6]. **d.** Photo of Taylor vortex flow in laboratory setup (top-side) with eccentric rotating cylinder. The bubble formation and layer formation can be clearly seen. **e.** Photo of shiny silvery surface layer on top of dispersion after mixing 10 min. @ 1800 rpm.