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Effect of system parameters on the size distributions of hollow nickel microspheres produced by an ultrasound-aided electrical discharge machining process

Yifan Liu[a], Xianglong Li[a,*], Fushi Bai[a], Jian Chen[b], Yantao Wang[a], Nan Liu[a]

[a] School of Manufacturing Science and Engineering, Sichuan University, Chengdu 610065, China
[b] School of Mechanical and Manufacturing Engineering, University of New South Wales, Sydney 2052, Australia

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A B S T R A C T

Ultrasound-aided electric discharge machining (EDM) is an emerging technology for producing hollow nickel microspheres. This technology combines traditional EDM with the cavitation and vibration effects of ultrasound to produce hollow microspheres. In this paper, ultrasound-aided EDM was carried out in a kerosene medium (the working solution). The effects of various parameters on the sizes of microspheres were investigated using scanning electronic microscopy (SEM). Smileview software was used to measure the sizes of the microspheres. Originpro software was used for statistical analysis to determine the size distributions of the microspheres. To study the effects of the system parameters on the sizes of the microspheres, we first investigated the necessity of using an ultrasonic wave with EDM. After comparing the experimental results with and without the ultrasonic field, we found that ultrasound-induced cavitation and vibration effects reduced the diameters of the microspheres. We then studied the effects of several electrical parameters, including the arc current, pulse width, and gap voltage, on the sizes of the microspheres at an ultrasound frequency of 40 kHz. Smaller microspheres could be obtained by lowering the arc current, pulse width, and gap voltage.

1. Introduction

The preparation of metallic microspheres has become a hot research topic in recent years. Many researchers (Du, Jiang, & Li, 2013; Kehoe, Kilcup, & Boyd, 2012; Liu et al., 2013) have tried to apply chemosynthetic methods to prepare various types of microspheres. More recently, electric discharge machining (EDM) has been widely used to prepare metallic microspheres (Berkowitz et al., 2003, 2004; Cabanillas, López, Pasqualini, & Cirilo Lombardo, 2004; Cabanillas, 2007; Carrey, Radousky, & Berkowitz, 2004; Song, Li, & Zhang, 2011; Vasudevamurthy & Knight, 2007). Vasudevamurthy and Knight (2007) used EDM to prepare carbonized uranium, but he focused only on the geometrical shapes, sizes, and influencing factors of the microspheres, rather than fully exploring the mechanism by which they form. Berkowitz et al. (2003, 2004) also used EDM to prepare microspheres. However, they used vacuum tight equipment in their experiments, which made the experiments complicated, costly, and difficult to reproduce. Cabanillas et al. (2004) and Cabanillas (2007) used deionized water as a dielectric medium for the production of metallic uranium molybdenum microspheres. A rotating electrode made of uranium molybdenum alloy was applied within an electric discharge machine, which was capable of delivering an arc of 25 A with varying pulse widths. Song et al. (2011) investigated the surface morphologies of microspheres for different electrical parameters. Their results implied that bubbles present in solution may help to decrease the microsphere diameters.

To better understand the effects of the system parameters on the size distributions of hollow nickel microspheres, it is necessary to review the process of EDM. In EDM, an electrical current produces electrical discharges that locally melt a material on the surfaces of two electrodes. This consequently causes the superheated molten material to escape from the molten crater. The molten metal exists mainly in liquid and gas forms. During this process, the working solution between the two electrodes is gasified to generate very small bubbles (Khanra, Pathak, & Godkhindi, 2007). Most of the molten metal is ejected to form spheres when it comes in contact with the cold dielectric solution or its vapor. If the gasiform and molten metallic crystals coat the gas bubbles as they are ejected, hollow microspheres will be formed as the heated metallic crystals

* Corresponding author. Tel.: +86 28 85466630.
E-mail address: lixianglong@scu.edu.cn (X. Li).

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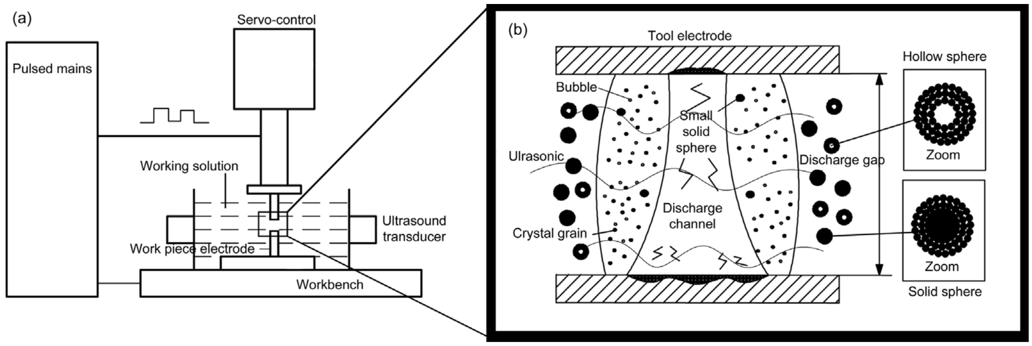

Fig. 1. (a) The schematic of experimental set-up and (b) the phantom image of formation mechanism.

rapidly cool and condense. In this paper, we incorporated ultrasonic wave into the dielectric liquid to deliver sufficient amount of bubbles in the working solution by virtue of its cavitation effect and to prevent the gasiform and molten metallic crystals from clustering together due to ultrasound vibration, thereby obtaining much smaller nickel microspheres. A series of experiments were carried out and the samples were collected and observed by SEM. Through careful analysis of the experimental data and influencing factors, we determined the optimal electrical parameters for forming smaller microspheres by ultrasound-aided EDM. Our data can be used to guide future research.

2. Materials and methods

Two identical strips of metallic nickel (nickel content > 99.9%, Tianjin Chengshuo Steel Trading Co., Ltd., Tianjin, China) were selected as the electrodes. The cross-sectional area of each nickel electrode was 14 cm^2. The experiments were performed in a numerical control EDM machine E46PM (Jiangsu Excellent Numerical Control Equipment Co., Ltd., Jiangsu, China), with a variable electrical current ranging from 1.5 to 60 A, a variable pulse width ranging from 2 to 1200 μs, and a variable gap voltage ranging from 30 to 120 V. The medium used for the ultrasound-aided EDM experiments was kerosene with boiling point ranging from 180 to 310 °C and density of 0.780 g/cm^3. Other dielectric media, such as, deionized water, and emulsified oil, have been used in our studies; however, we found that kerosene was the best working solution for our application. It is worth pointing out that the effects of varying the viscosity, density, and temperature of the working solutions on the diameters of microspheres were not investigated in this paper. After the nickel microspheres were prepared by EDM and collected with an NdFeB magnet (N42SH, 12*4.25*1.25, Shenzhen Tianlihe Magnetism Trading Co., Ltd., Shenzhen, China), they were washed and cleaned with petroleum ether (melting(II), AR, boiling point 60–90 °C, 500 mL, Hangjia Bio-pharmaceutical Technology Co., Ltd., Chengdu, China).

To obtain smaller microspheres and more bubbles, an ultrasound field was produced in the electric discharge machine by two ultrasonic oscillators, which were attached on opposite sides of the processing box. The experimental set-up and the phantom image of the formation mechanism are depicted in Fig. 1.

3. Results and discussion

3.1. Effect of the ultrasonic wave

As the ultrasonic waves propagate, the suspended microspheres contained in the working solution oscillate. Under the influence of Brownian motion, van der Waals attraction, and fluidic stirring, the crystals move close to each other and collide. They then aggregate to form larger microspheres. However, as the cavities collapse, impact pressures are generated (Guo, Khoo, Teo, & Lee, 2013). These powerful impact forces repeatedly shock the microspheres and disaggregate them. Consequently, the microspheres separate from each other and precipitate as smaller microspheres (Jin, Bi, & Zhang, 2011). The ultrasonic wave may also break the molten or gasified metal into smaller parts before it cools (Chen & Chen, 2003). The cavitation effect of ultrasound can also generate additional bubbles in the working solution (Hayakawa, Doke, Itoigawa, & Nakamura, 2010; Mohammad & Mobadersany, 2013). These additional bubbles can improve the combination rate between the molten or gasified metal and the bubbles. Fig. 2 shows SEM micrographs of the nickel microspheres under an ultrasonic wave.

Four experimental groups (A1–D1) were performed without ultrasonic waves (the traditional EDM process). For comparison with the same electrical parameters used in the first four

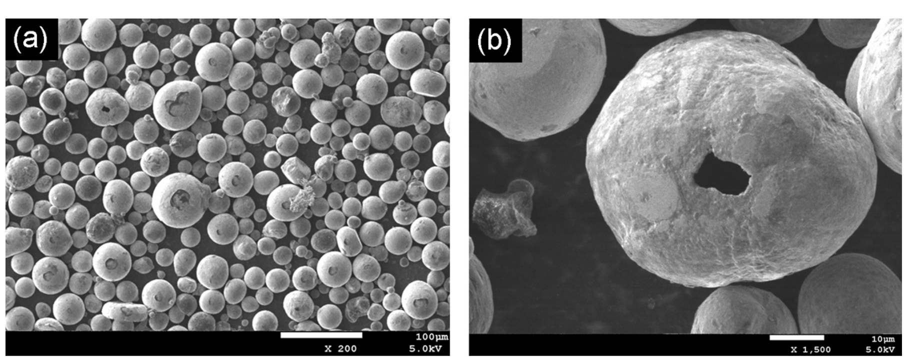

Fig. 2. (a) SEM micrograph showing a group of spherical microspheres at low magnification under ultrasonic wave; (b) SEM micrograph of a thin hollowed sphere at high magnification.

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