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Short communication

Ultrasonic vibration-assisted laser atomization of stainless steel

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ABSTRACT

In this paper, a novel ultrasonic vibration-assisted laser atomization process for producing fine metallic powder with average particle diameter of about 75–95 μm is proposed. The process involves irradiation of a high power continuous wave laser on a consumable metallic substrate vibrating at an ultrasonic frequency. The laser irradiation on the vibrating substrate causes surface melting and expulsion of fine droplets. Preliminary results are presented for the atomization of AISI 316 stainless steel using CO_2 laser power of 950 W and vibration frequency of 20 kHz. The average particle size and size distribution is not significantly influenced by vibration displacement consistent with capillary wave theory of atomization. The microstructure of the larger atomized particles showed fine dendritic structure at the surface and shrinkage porosity at the center of particles indicating multiple surface nucleation for solidification.

1. Introduction

Recently, the demand for high quality metal powder has grown rapidly with the development of metal additive manufacturing (AM) technologies [1]. The metal AM technologies are being increasingly adopted for rapid prototyping and series production in diverse industrial sectors. With the established market in powder metallurgy (P/M) and plasma/thermal spraying and the emergence of new applications such as additive manufacturing, the demand for metal powder is projected to grow rapidly in coming years. High-throughput and low-cost production of metal powder with consistent quality and properties for desired applications is a key challenge in the powder manufacturing. Conventional powder preparation techniques such as chemical, mechanical, electrolytic, and atomization (gas, water/oil, vacuum, centrifugal, and ultrasonic capillary wave atomization) processes have been extensively used for the production of metallic powders [2]. Among these techniques, atomization is one of the most versatile techniques for the production of metal powder over a wide range of particle distributions and with high-throughput for several metallic materials, including several steels, aluminum alloys, titanium alloys, and superalloys. While average particle size and size distribution of powder particles can be controlled by varying atomization parameters, the atomization processes require high energy to supply water at high pressure (water atomization) or expensive inert gases (gas atomization), resulting in a very low overall energy efficiency (~3–4%) [3]. The utilization of the water atomization is often restricted as water reacts with the highly reactive metals (titanium and superalloys) and results in formation of undesirable surface oxide layer on powder particles [1]. Also, the conventional atomization processes that take large batch sizes are not very well suited for low volume production of specialized alloy powder for research and development.

Metal powder production techniques such as centrifugal and ultrasonic atomization based on expulsion of molten material/melt film have also been investigated especially for low melting materials [4]. In centrifugal atomization, a stream of molten material is dispensed on a rotating surface and the centrifugal forces cause expulsion of melt into droplets. On the other hand, in the ultrasonic atomization, capillary waves and/or cavitation forces break up the liquid metal film on the surface of the vibrating surface (ultrasonic horn) causing expulsion of fine droplets [5]. Atomized particle size depends on the thermophysical properties of the liquid metal and ultrasonic vibrations parameters. The ultrasonic atomization yields narrower particle size distribution and spherical particles. Due to rapid cooling rates, the particles produced by these techniques also exhibit very good compositional homogeneity and microstructural refinement. In one of the earliest studies on ultrasonic atomization of the metal melts, Lierke and Griesshammer reported particle size of 43 μm and 39 μm for melts of Sn and Pb, respectively, at the ultrasonic vibration frequency of 20 kHz [6]. While the ultrasonic atomization has been mostly investigated for low melting point alloys such as soldering alloys, the processes are also becoming attractive for high melting point alloys with the development of inert rotating/vibrating surface materials.

Recently, pulsed laser ablation in liquid media has been used to produce metallic nanoparticles (up to 5 nm in diameter) [7]. However, the laser ablation process is not suitable for the production of micrometer-sized metal particles. In this paper, a novel ultrasonic

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vibration-assisted laser atomization process is reported for the production of fine metal powder particles. The process involves continuous wave (CW) CO_2 laser irradiation on a consumable metallic substrate vibrating at an ultrasonic frequency (20 kHz). The laser irradiation of the vibrating surface causes surface melting and subsequent expulsion of the melt into fine droplets. Preliminary results on the particle characteristics are presented and discussed for the ultrasonic vibration-assisted laser atomization of AISI 316 stainless steel.

2. Material and methods

The schematic of the ultrasonic vibration-assisted laser atomization is presented in Fig. 1. The set-up consisted of an ultrasonic vibration system with a 13-mm diameter threaded Ti-alloy probe (Sonics & Materials, Inc., Newtown, CT) and a continuous wave CO_2 laser (Ferranti, Manchester, UK). For producing powder of AISI 316 stainless steel, a 3-mm thick steel specimen was screwed on the ultrasonic probe. The surfaces of the steel specimens were polished using 400 grit SiC papers followed by sand blasting to increase laser absorption. The steel specimens were vibrated at the frequency of 20 kHz and ultrasonic power outputs of 20, 30, and 40% corresponding to vertical (longitudinal) vibration displacements of 23, 37 and 51 μm, respectively. The laser beam operating with power output of 950 W and beam diameter of 2.15 mm was scanned at the speed of 30 mm/s on the vibrating surface of the steel specimen. The laser irradiation causes surface melting of the vibrating specimen, resulting in droplet ejection in the form of fine metal powder particles. A co-axial argon shroud gas was used to protect the melt pool. The ultrasonic vibration displacements used in this investigation were the optimized parameters resulting in efficient melt expulsion at the given ultrasonic vibration frequency (20 kHz) and the laser power (950 W). A scanning electron microscope equipped with energy-dispersive X-ray spectroscopy (EDS) was used to characterize the microstructural and compositional features of the atomized powder particles. For cross-sectional microstructure analysis, the powder particles were mounted in polymer resin to prevent surface damage during subsequent polishing. The sample preparation consisted of a series of polishing on SiC papers (grit size up to 1200) and final polishing on cloth using alumina solution (particle size up to 0.3 μm). X-ray powder diffractometer (XRD) operating with Cu Kα ($\lambda = 1.54178$ Å) radiation was used for identifying the phases in the atomized steel powder.

3. Results and discussion

In the proposed ultrasonic vibration-assisted laser atomization, a continuous wave CO_2 laser irradiation causes surface melting of the desired consumable metallic substrate that is vibrating at an ultrasonic frequency (Fig. 1). While the surface tension effects tend to keep the melt pool in place, the ultrasonic vibrations of the substrate tend to destabilize the melt pool. When the volume of the melt pool reaches a critical size, the ultrasonic vibrations break the surface melt film and causes ejection of the melt into fine droplets. The melt droplets undergo rapid solidification to form solid metal powders. Fig. 2(a) shows SEM micrographs of the AISI 316 steel powder particles produced using ultrasonic vibration-assisted laser atomization with laser power of 950 W and vibration displacements of 23, 37, and 51 μm at the ultrasonic frequency of 20 kHz. The metallic powders prepared by ultrasonic vibration-assisted laser atomization have a highly spherical shape. The high magnification SEM micrographs of the particles show fine dendritic structure on the surface of the particles and interdendritic porosity (Fig. 2). As it can be seen in Fig. 2, the particle size distribution peaks at about 100–125 μm for the atomized particles. The average size of the particles were 93 ± 21 μm, 75 ± 19 μm, and 84 ± 24 μm for vibration displacements of 23, 37, and 51 μm, respectively. In general, the intense ultrasonic vibrations with higher displacements resulted in finer atomized particles possibly due to efficient ejection of smaller droplets of melt volumes.

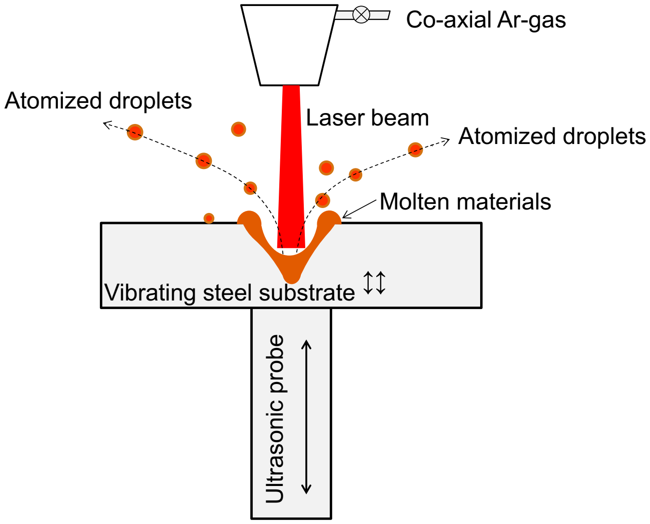

Fig. 1. Schematic of the ultrasonic vibration-assisted laser atomization setup.

In ultrasonic atomization, several mechanisms such as cavitation wave and capillary wave cause the disintegration of the surface liquid film [8]. In cavitation-wave mechanism, acoustically driven bubble oscillations beneath the liquid surface cause the expulsion of droplets. The cavitation forces can also cause non-uniform disintegration of the liquid film, ejecting larger chunks of liquid metal. It has been reported that when acoustic cavitation is the main atomization mechanism, irregularity in the shape and size of the atomized droplets is observed [9]. On the other hand, in capillary wave mechanism, the liquid film on the vibrating surface becomes unstable and creates surface capillary wave (ripples) [10]. The amplitude of the capillary wave continuously increases, and eventually the wave peaks break from the liquid film and eject as droplets. Based on Navier-stokes equation, the correlation between wavelength of the capillary waves (λ_s) and atomization parameters is given by [11]:

$$\frac{2}{\pi f^2 \lambda_s}\left(4\frac{\sigma\pi^2}{\rho{\lambda_s}^2}+g\right)\tanh\left(\frac{2\pi l_m}{\lambda_s}\right)+0.02\left[\frac{\pi a_0}{\lambda_s}\tanh\left(\frac{2\pi l_m}{\lambda_s}\right)\right]^{1/2}-1.04=0, \quad (1)$$

where g, l_m, a_0, σ, ρ, and f are gravitational acceleration (m/s^2), liquid film thickness (m), vibration amplitude (m), surface tension of the liquid (N/m), density of the liquid (kg/m^3), and frequency of ultrasonic vibrations (Hz), respectively. It has also been reported that if the liquid film is thin ($\tanh(\frac{2\pi lm}{\lambda_s})\cong 1$) and the impact of gravitational force is negligible compared to the ultrasonic force, Eq. (1) reduces to the Lang's equation [12]:

$$\lambda_s = \left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \quad (2)$$

The capillary wave mechanism results in the formation of highly spherical atomized particles with good correlation between average particle size and wavelength of capillary waves. It has been reported that the average diameter of the ejected droplets (D) during ultrasonic atomization is about 0.34 times of the wavelength of the capillary wave (λ_s) on the liquid film and is given by: [10].

$$D = 0.34\left(\frac{8\pi\sigma}{\rho f^2}\right)^{1/3} \quad (3)$$