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Process modeling pressure-swirl-gas-atomization for metal powder production

Xing-gang Li[a,c,*], Udo Fritsching[a,b]

[a] Foundation Institute of Materials Science (IWT), Bremen, Germany
[b] Particles and Process Engineering, University of Bremen, Bremen, Germany
[c] General Research Institute for Nonferrous Metals (GRINM), Beijing, China

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ABSTRACT

The paper aims at integral process modeling and simulation of the pressure-swirl-gas-atomization process for metal powder production. A numerical analysis is applied in this way to the atomization and spray process of a molten metal for metal powder production. The primary disintegration process of swirling conical sheets of the molten metal is described by the Volume of Fluid (VOF) approach, while the subsequent droplet spray process is simulated through the Eulerian-Lagrangian approach by taking the secondary breakup of produced droplets as well as in-flight spray phenomena such as drag and droplet solidification into account. The characteristics of liquid sheet fragmentation such as primary droplet size and velocity are derived and compared with measurements. The coupled simulation is realized by setting the outcomes of liquid sheet fragmentation as the initial conditions for the droplet spray process simulation. An assessment of classical secondary breakup models is shown in comparison with measurements. The droplet solidification behaviour in a spray process is investigated. Finally, the powder particle size distribution will be derived from the process modeling and simulation.

1. Introduction

Metal powders are the basis of powder metallurgy processes with various applications, such as sintering, compaction, thermal spray coating and soldering of metallic parts. The emerging technological field of Additive Manufacturing (AM) typically needs specifically tailored materials and particles, especially metal powders with precisely optimized size, shape and morphology (Gökce et al., 2015). Gas atomization technology is the most widely used method to produce fine spherical metal powders. In a gas atomization process, a hot molten metal stream has extensive heat and momentum exchange with high pressure cold gas jets, which give rise to high cooling rates and deep undercooling to the atomized metal droplets. The produced powder particles have reduced segregation and very fine microstructure which improves material properties such as strength, toughness, hardness, and corrosion resistance. Two most widely used nozzle systems in industry are close-coupled type and free-fall type, in both of which a round liquid jet is atomized by a high speed atomization-gas stream surrounding the liquid jet. In a close-coupled configuration, gas jet hits the molten metal immediately after it comes out of the melt nozzle. This configuration can produce very fine powder particles but is more susceptible to freezing of the melt at the nozzle tip. In a free-fall configuration, the molten metal falls freely for some distance in the direction of gravity (typically around 100 mm) before being hit by the atomization gas. This configuration generally produces relatively coarse particles.

In this paper a recently developed powder production route utilizing pressure-swirl-gas-atomization (PSGA) in Lagutkin et al. (2004) is investigated. The principle of the PSGA process is illustrated in Fig. 1. This atomization technique combines pressure-swirl-atomization as a pre-filming step and gas atomization. The molten metal, on which an overpressure (Δp_l) is imposed, leaves the nozzle exit of a pressure-swirl-nozzle as a conical hollow cone due to the rotation and centrifugal forces. The diameter of the melt nozzle exit (D_0) is 1–2 mm. Initially the thickness of the melt lamella is 200–300 μm when the melt leaves the nozzle. With increasing distance from the nozzle the thickness of the lamella declines until primary breakup starts and results in the formation of ligaments and droplets of several hundred micrometers in diameter (primary atomization). These primary fragments are still in a full liquid state and then atomized by discrete high velocity gas streams from a ring

* Corresponding author at: Foundation Institute of Materials Science (IWT), Bremen, Germany.
E-mail addresses: lixinggang@grinm.com, xing-gangli@163.com (X.-g. Li), ufri@iwt.uni-bremen.de (U. Fritsching).

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Nomenclature

c	Speed of sound [$m\,s^{-1}$]
C_b, C_d, C_f, C_k	Coefficients in TAB model [–]
C_d	Drag coefficient [–]
C_D	Liquid discharge coefficient [–]
Co	Courant number [–]
C_p	Specific heat capacity at constant pressure [$J\,kg^{-1}\,K^{-1}$]
C_v	Specific heat capacity at constant volume
d or D	Diameter [m]
$d_{50,3}$; d_{32}	Mass median diameter, MMD [m]; sauter mean diameter SMD [m]
f	Volume fraction [–]
g	Gravitational acceleration [$m\,s^{-2}$]
h	Film thickness [m]
ΔH_f	Latent heat [$J\,kg^{-1}$]
k	Turbulence kinetic energy [$m^2\,s^{-2}$]
K_{br}, k_1, k_2	Coefficients in ETAB model [–]
K_v	Coefficient [–]
L	Lenghth [m]
m	Mass [kg]
M	Molecular weight [$kg\,mol^{-1}$]
$\dot{M}$	Mass flow rate [$kg\,s^{-1}$]
Nu	Nusselt number [–]
Oh	Ohnesorge number [–]
p	Pressure [Pa]
Pr	Prandtl number [–]
r	Radius [m]
R	Ideal gas constant [$J\,mol^{-1}\,K^{-1}$]
Re	Reynolds number [–]
t	Time [s]
T	Temperature [K]
U	Velocity [$m\,s^{-1}$]
We	Weber number [–]
x, y, z	Cartesian coordinates [m]
x	Droplet deformation [m]
X	Area ratio of air core at nozzle exit to nozzle exit section
y	Dimensionless droplet deformation [–]
α	Spray angle [°]
κ	Specific capacity ratio Cp/Cv [–]; interface curvature [m^{-1}]
λ	Thermal conductivity [$W\,m^{-1}\,K^{-1}$]
μ	Dynamic viscosity [Pa s]
μ, σ	Coefficients in root normal distribution
ρ	Mass density [$kg\,m^{-3}$]
σ	Surface tension [$N\,m^{-1}$]
τ_E	Eddy life time [s]
τ_I	Particle-eddy interaction time [s]
τ_r	Residence time in eddy [s]
ω	Specific turbulence dissipation rate [s^{-1}]; frequency [s^{-1}]

Subscript

0	Initial condition; stagnation state; state at liquid nozzle exit
a	Ambient condition
b	Breakup
corr	Corrected
crit	Critical
d	Droplet
def	Deformation
e	State at gas nozzle exit
g	Gas
l	Liquid
r	Radial direction
rel	Relative
s	Solid; stable
t	Tangential direction
trans	Transition
z	Axial direction

gas nozzle which surrounds the lamella (secondary atomization). The resultant secondary droplets are mainly directed to the centreline of the atomizer axis and subsequently solidify in flight to form metal powders. The PSGA technique has been used to produce fine metal powders with small median diameters and narrow size distributions by Lagutkin et al. (2004), as well as metal-matrix-composite (MMC) particles by Li et al. (2016).

The process conditions such as feed-material properties, nozzle selection, operation parameters and spray-tower geometry determine the final powder properties such as size, shape and morphology through influencing liquid and/or droplet atomization and cooling in a spray process. Aim of the paper is to correlate the process conditions to the powder properties through integral modeling and simulation of the PSGA process. This can be achieved based on multiphase CFD-continuum models by taking account of liquid fragmentation and atomization phenomena and spray transport phenomena as well as the consolidation of the droplets to form solid particles.

The Eulerian-Lagrangian (EL) formulation is the most intuitive approach for spray processes being characterized as dispersed multiphase flow. In this approach, the continuous gas phase is described by the standard Eulerian conservation equations. The behaviour of the dispersed phase is described based on the Lagrangian discrete droplet method (DDM), i.e., the transport of the dispersed phase is calculated by tracking the trajectories of a certain number of representative parcels through the calculated flow field. A parcel consists of a number of particles or droplets, and it is assumed that all the particles or droplets within one parcel have the same physical properties and behave equally when they move, break up, and solidify. The coupling between dispersed and continuous phases is realized by source-term exchange for mass, momentum, energy and turbulence. Various sub-models accounting for the effects of droplet breakup, aerodynamic drag, turbulent dispersion, collision,

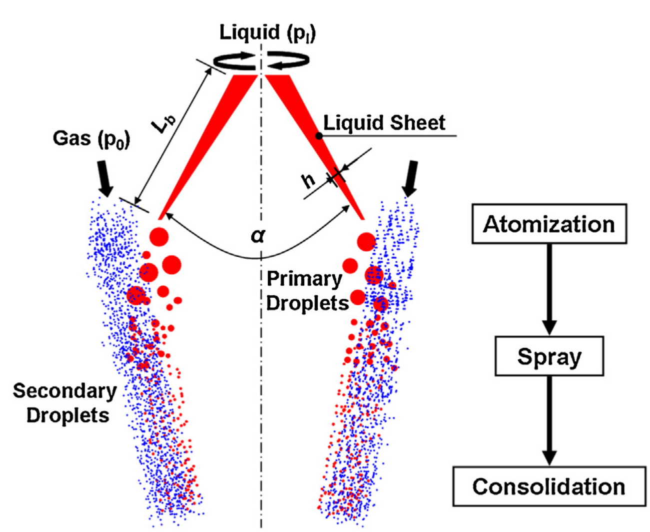

Fig. 1. Illustration of pressure-swirl-gas-atomization process.