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Melting of Steel Spherical Particle in Its Own Liquid: Application to Cladding

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Blown-powder laser cladding finds its application in manufacturing industries to improve the surface properties of metallic mechanical parts. In the blown-powder laser-cladding process the powder particles go into the superheated melt pool formed by melting of the powder and become the integral part of the substrate coating upon solidification as the laser beam moves away. In the present study, two-dimensional axisymmetric Navier–Stokes and energy equations are solved using the finite volume method to predict the time required for a steel sphere to melt in a melt pool of the same material. The effect of forced convection, characterized by a Reynolds number, and superheat of the melt pool, characterized by a Stefan number, have been studied in detail for a Prandtl number of 0.13. The effect of buoyancy is neglected for the present investigation. It is found that the effect of forced convection on melting time reduction is more pronounced for the low Stefan number case. The rate of melting of the sphere with time under different conditions is also presented. Finally, the heat transfer characteristic is presented by the correlation of a Nusselt number with a Reynolds number and a Stefan number for a Prandtl number of 0.13. The decrease in size of the particle and its change in shape have been presented along with the evolving velocity and temperature field around the particle.

Nomenclature

A = porosity function, kg/m^2 s
f_l = liquid fraction
Gr = Grashof number
h = specific sensible enthalpy, J/kg
h_c = heat transfer coefficient, W/m^2 °C
k = thermal conductivity, W/m^2 °C
Nu = Nusselt number
Pr = Prandtl number
p = pressure, N/m^2
R = radius of solid sphere, m
Re = Reynolds number
r, z = cylindrical coordinate system, m
Ste = Stefan number
t = time, s
U_∞ = freestream velocity along z direction, m/s
$\mathbf{V}$ = velocity vector, m/s
v_r, v_z = velocity component in r, z directions, m/s
α = thermal diffusivity, m^2/s
Δh_{sl} = specific latest heat of fusion, J/kg
ν = kinematic viscosity, m^2/s
ρ = density, kg/m^3
τ = dimensionless time
ψ = stream function, kg/s

Subscripts

D = diameter
l = liquidus
s = solidus
0 = initial condition, that is, at $t = 0$
∞ = freestream condition

Superscript

$\star$ = dimensionless variable

I. Introduction

LASER cladding is one of the techniques which improves the surface properties of metallic mechanical parts, such as the resistance against wear and corrosion. Laser cladding with powder feed has established itself in practice. Some of the applications include the enhancement of the corrosion resistance of the gas turbine blades and improvement of the wear resistance of diesel engine exhaust valves. In the blown-powder laser-cladding process powder particles of diameter 20 to 200 μm are injected into the superheated melt pool with velocity in the range of 0.1–10 m/s. The powder particles melt and mix with the surrounding molten material formed by melting of the powder. Knowledge of the convective heat transfer from a melting metal sphere under such conditions is important for understanding this transport process.

Melting of a solid particle in a superheated fluid of the same or different material has been studied extensively. Kreith et al. [1] performed an experimental and theoretical investigation of rotating metallic spheres in liquid mercury and suggested a correlation for forced convection. Hsu [2] has given an expression for the theoretical Nusselt number for the cases of heat transfer to liquid metals flowing past a single sphere, and flowing past an elliptical rod considering potential flow around the solid object. Anselmo et al. [3] have presented the theoretical and experimental results on the melting of both fully and partially immersed silicon spheres. Numerical and experimental investigations on the melting time of a solid sphere immersed in liquid aluminum and steel have been carried out by Argyropoulos and Mikrovas [4] and Argyropoulos et al. [5]. They have given correlations for forced and natural convection based on the measurement of the melting times of the spheres. More recently, Melissari and Argyropoulos [6,7] have conducted an extensive numerical and experimental analysis of the melting of pure aluminum and AZ91 magnesium alloy in the liquid bath of the same material. In another paper Melissari and Argyropoulos [8] found the correlation for forced convection correlating the Nusselt number to the Reynolds number and the Prandtl number.

There are a few studies on the melting dynamics of nonmetallic spheres at different convective regimes. Kranse and Schenk [9] performed experiments on the free convection melting of a submerged benzene sphere in an excess amount of its own liquid. The

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