International Journal of Psychosocial Rehabilitation, Vol. 23, Issue 04, 2019
ISSN: 1475-7192

Analytical Models for the Estimation of Effect of the Spray Angle on a Subcooled Target

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Abstract--- *Since its beginnings nearly a century ago, plant superintendents and maintenance personnel have relied on thermal spray technology as a cost-effective means to repair worn components and incorrectly machined parts for light and heavy industrial equipment. The manufactures of thermal spray equipment and materials have continued their efforts to make thermal spray technology more attractive by creating new spray systems and materials. As a result, it is now possible to tailor a coating solution to fit a customer's needs. Thermal sprayed coatings are used extensively for a wide range of industrial applications. The technique generally involves the spraying of molten powder or wire feedstock, the melting technique achieved by oxy-fuel combustion or an electric arc (plasma). The molten particles are accelerated by the flame, followed by impacting onto a properly prepared substrate, usually metallic. Solidification occurs at rates akin to those obtained in Rapid Solidification Technology. Thus, the as-sprayed deposit is ultra-fine grained. Having the properties associated with such microstructures. The materials which are sprayed include most metal alloys and ceramics. In fact, virtually any material can be thermal sprayed as long as it does to decompose prior to melting. In this paper, we present a simple analytical mathematical model for the estimation of the maximum splat diameter of an impacting droplet on a subcooled target. The model uses an energy conservation argument, applied between the initial and final drop configurations, to approximately capture the dynamics of spreading. The effects of viscous dissipation, surface tension, and contact angle are taken into account. Tests against limited experimental data at high Reynolds and Weber numbers indicate that accuracy of the order of 5% is achieved. Also the effect of the spray angle on the maximum splat diameter can be calculated. Thus once the maximum splat diameter is found the thermal spraying process can be optimized for maximum efficiency. Various parameters like the initial droplet velocity, contact angle etc. can be pre-determined, thus making the process cost-efficient.*

Keywords--- *Analytical Models, Spray Angle, Subcooled Target, Pre-determined.*

I. INTRODUCTION

In recent years various simple analytical models for the estimation of the maximum splat diameter of an impacting droplet on a subcooled target have been proposed. Such models could prove very useful as preliminary design tools in the rapidly developing field of microfabrication. They can additionally facilitate the understanding of the couple droplet spreading and solidification dynamics, which will lead to improvement in microfabrication quality. In this paper we present a model that accounts for the effects of surface tension, contact angle, and solidification at the droplet-target interface.

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Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019

Consider a superheated liquid metal droplet of diameter D_o and at temperature $T_o > T_m$ impacting a subcooled solid substrate (temperature $T_w < T_m$) with velocity V_o. We are interested in the limit of small superheat, that is ($T_o - T_m$) → 0 where T_m is the melting temperature. When spreading stops, the droplet has reached the maximum splat configuration in the shape of a thin disk of diameter D, and height h. We assume that the material has partially solidified: a thin layer of thickness s (averaged over the diameter) at the substrate-droplet interface is now solid at (an average) temperature T, where $T_w < T < T_o$, and the remaining droplet material is molten at T_m The maximum splat ratio < is defined as $\xi = D_m/D_o$. One important assumption used in this work is that the droplet arrest is not governed by solidification, that is the effect of heat transfer and solidification is only secondary to the spread process.

In the isothermal case the target and droplet are at the same temperature ($T_o = T_w$) and negligible heat exchange takes place between the two.

II. THE MAXIMUM SPLAT DIAMETER

The maximum spread diameter, D_m can be estimated by using an energy conservation argument: the energy at every instant in time, and hence at the maximum splat diameter configuration (configuration 2), has to equal the initial energy of the drop (configuration 1). This initial energy is equal to the sum of the kinetic energy (***KE₁***) and the surface energy (***SE₁***) of the impacting droplet. The kinetic energy is given by:

$$KE_1 = \left(\frac{1}{2}\rho V_o^2\right)\left(\frac{1}{6}\pi D_o^3\right)$$

Where $\boldsymbol{\rho}$ is the liquid drop density. The initial surface energy is given by:

$$SE_1 = \pi D_o^2 \gamma$$

Where γ (gamma) is the surface tension coefficient for the drop in the ambient environment. The energy at the maximum splat configuration consists of the energy dissipated through the action of viscosity during the spreading process and the surface energy of the maximum splat configuration. The first term has been shown (Pasandideh-Fard et al., 1996) to (approximately) equal.

$$W = \frac{\pi}{3}\rho V_o^2 D_o D_m^2 \frac{1}{\sqrt{R_e}}$$

Where, $R_e = \rho V_o D_o / \mu$ is the Reynolds's number. This estimate is obtained by assuming an axisymetric stagnation point flow which in the high Reynold limit can be approximated by a viscous boundary layer of thickness $\delta = 2D_o / \sqrt{R_e}$ and potential flow outside this boundary layer.

The surface energy (***SE₂***) is estimated by assuming that the final configuration approximates a thin disk. It is shown by Collings et al. (1989) that given the contact angle (θ_a), and the disk-shape geometry assumption with diameter D_m, and height h that is small compared to D_m

Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019

$$SE_2 = \frac{\pi}{4} D_m^2 \gamma (1 - \cos\theta_a)$$

Equating,

$$KE_1 + SE_1 = W + SE_2$$

Substituting the values,

$$\left(\frac{1}{2}\rho V_o^2\right)\left(\frac{1}{6}\pi D_o^3\right) + \pi D_o^2 \gamma = \frac{\pi}{3}\rho V_o^2 D_o D_m^2 \frac{1}{\sqrt{R_e}} + \frac{\pi}{4} D_m^2 \gamma (1 - \cos\theta_a)$$

$$D_m = D_o \sqrt{\frac{\frac{\rho V_o^2 D_o}{12} + \gamma}{\frac{\rho V_o^2 D_o}{3\sqrt{R_e}} + \frac{\gamma(1-\cos\theta)}{4}}}$$

Where V_o is equal to V_N in our case.

Assuming initial droplet velocity to be constant we get a relation between:

- Maximum splat diameter (D_m)
- Initial droplet diameter (D_o)
- Contact angle (θ_a)

III. RESULTS

- Tin and Stainless Steel were used in the simulation. The impinging droplet was of Tin (Sn) and the substrate was made up of Stainless Steel.
- The properties for Tin and Stainless Steel are given below:

Droplet Initial Temperature:	519 K
Substrate Initial Temperature:	298 K
Solidus Temperature:	504 K
Liquidus Temperature:	506 K
Thermal conductivity of solid tin:	33.6 $W(mK)^{-1}$
Thermal conductivity of liquid tin:	62.2 $W(mK)^{-1}$
Thermal conductivity of Steel:	14.9 $W(mK)^{-1}$
Density of Steel:	7900 kg m^{-3}

Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019

Density of liquid tin: 6980 kg m^{-3}

Density of solid tin: 7200 kg m^{-3}

Droplet surface tension: 0.566 N m^{-1}

Specific heat of droplet: 244 J(kg K)$^{-1}$

Specific heat of Steel: 477 J(kg K)$^{-1}$

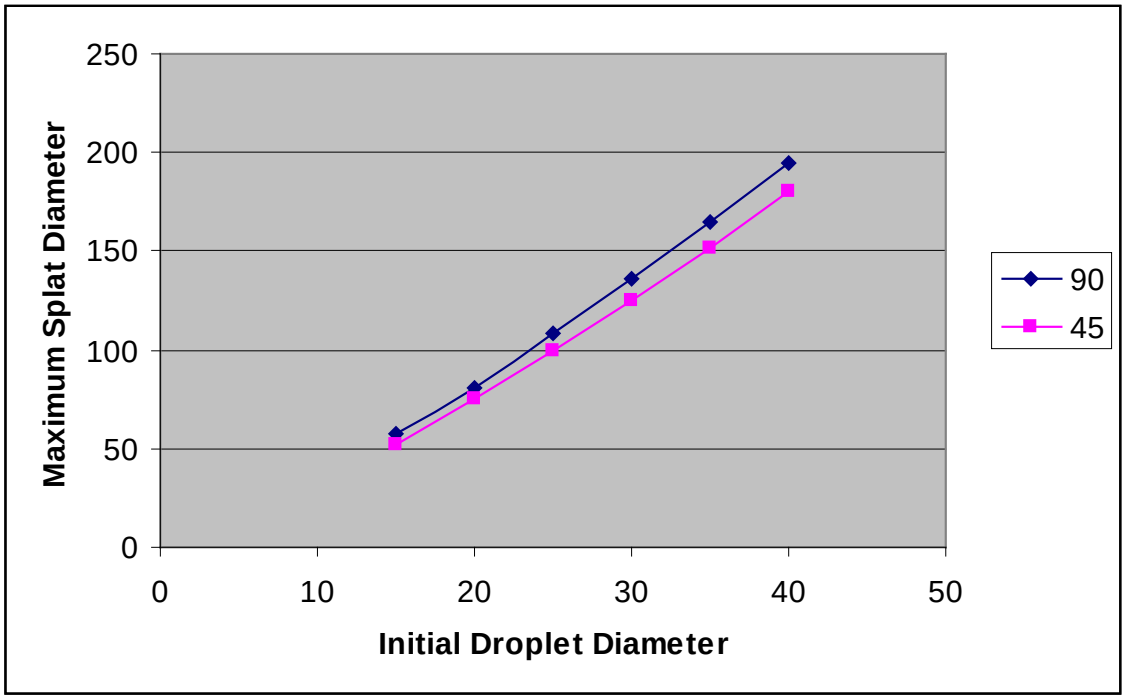
Viscosity of liquid Tin: 3×10^{-3} N.s m^{-1}

Latent heat of solidification: 58500 J kg^{-1}

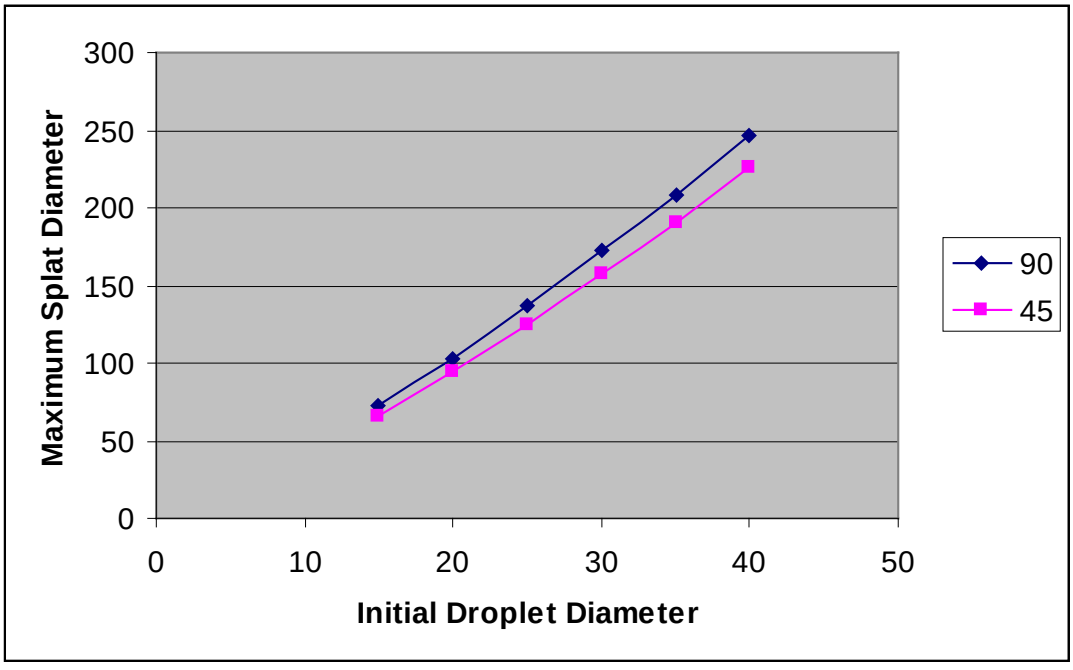
Initial Droplet Diameter $D_o(\mu m)$	***Initial Velocity*** V_o (m/s)	***Contact Angle*** θ_a	***Normal Velocity*** $V_N = V_o \cos\theta$	***Reynolds no.*** Re_N	***Maximum Splat Diameter*** $D_m(\mu m)$
15	100	90	100	3490	57
20	100	90	100	4653	81
25	100	90	100	5816	108
30	100	90	100	6980	136
35	100	90	100	8143	165
40	100	90	100	9306	195
15	100	45	70.71	2467	52
20	100	45	70.71	3290	75
25	100	45	70.71	4112	100
30	100	45	70.71	4935	125
35	100	45	70.71	5758	152
40	100	45	70.71	6580	180
15	250	90	250	8725	72
20	250	90	250	11633	103
25	250	90	250	14541	137
30	250	90	250	17450	172
35	250	90	250	20358	208
40	250	90	250	23266	246
15	250	45	176.77	6169	66
20	250	45	176.77	8225	95
25	250	45	176.77	10282	125
30	250	45	176.77	12338	158
35	250	45	176.77	14394	191
40	250	45	176.77	16451	226

Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019

Impact Velocity 100 m/s



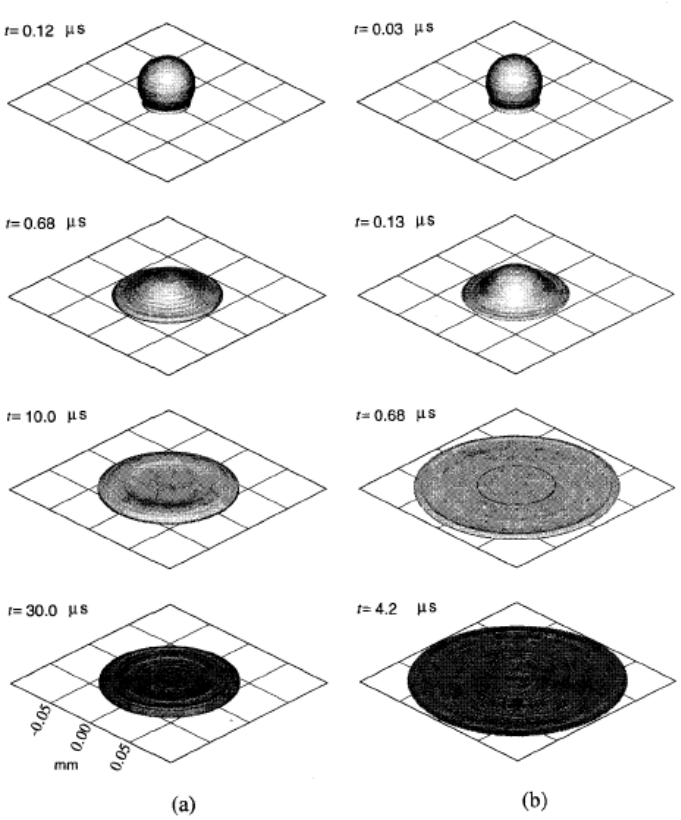
Impact Velocity 250 m/s



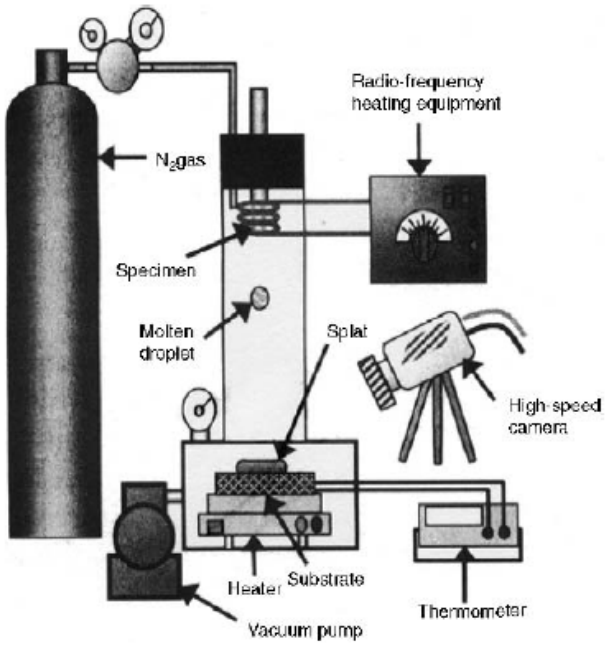
IV. SPLAT FORMATION PROCESS

Predicted Sequence of deformation and solidification for the tin droplet impinging on the steel substrate.

Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019

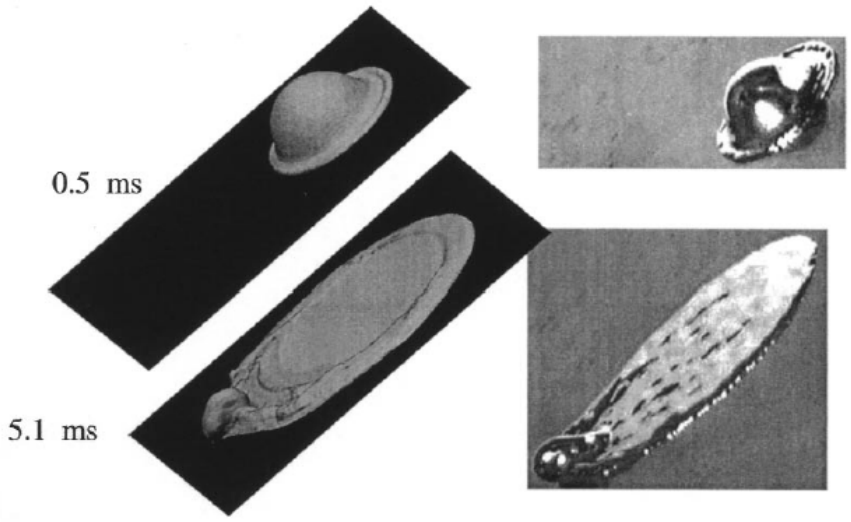


Predicted sequence of deformation and solidification for the alumina droplet; 50 μm diameter; 246°C initial temperature; 90 degrees contact angle; no contact resistance; (a) 100 m / s impact velocity; (b) 250 m/s impact velocity.



Schematic drawing of the experimental setup to study the impact of a millimeter-sized particle

Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019



Comparison of the predicted (left column) and photographs (right column) of the impact of tin droplet on stainless steel substrate. Droplet diameter 2.2 mm; impact speed 100 m/s; initial drop temperature 246 °C; initial substrate temperature 25 °C; incline angle 45°.

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Received: 08 Apr 2019 | Revised: 07 May 2019 | Accepted: 07 June 2019