

Review Article

Prediction of Thermal Behaviour in Spray Formed Slabs-A Review

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Abstract

By using this modelling and simulation, the temperature fields i.e. temperature at various points of the part, cooling rates and solidification characteristics of the part can be investigated and in addition the impact of process parameters and boundary conditions on the thermal profiles of part can be analysed. By doing this we can determine various mechanical properties without carrying out destructive testing quickly. We have to determine important process parameters for solving the heat transfer equation by finite difference method and obtain temperature at various points and times with the help of that solved equation and draw the temperature profiles with respect to position and time and then at last comparing modelling results with experimental results. The simulation results are in good agreement with experimental results.

Keywords: Spray forming, Mathematical Modelling, Simulation, Heat transfer equation.

1. Introduction

In recent years spray forming has been an emerging forming process for the production of near net shape products with the benefits that of rapid solidification, semi-solid processing etc. This spray forming processes combines the advantages of metal casting and powder metallurgy. Spray forming has minimized the multiple steps of powder metallurgy which includes processes like powder production, sieving, degassing and consolidation into a single processing step and still micro-structural characteristics remains the same. Figure 1.1, illustrates the schematic view of spray forming.

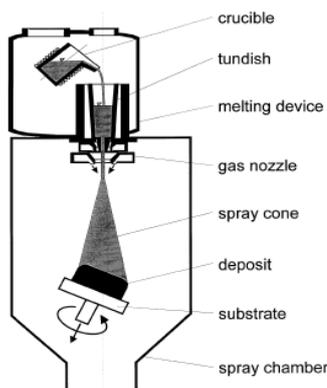


Fig 1.1 Schematic view of spray forming processes

The molten metal exits the furnace as a thin free-falling stream and is broken up into droplets by an annular array of gas jets, and these droplets then proceed downwards, accelerated by the gas jets to impact onto a substrate. 'The process is arranged such that the droplets strike the substrate whilst in the semi-solid condition, this provides sufficient liquid fraction to 'stick' the solid fraction together. Deposition continues, gradually building up a spray formed billets of metal on the substrates.'

In the spray forming processes the metal is heated in the crucible until the superheat temperature is reached and the molten metal is poured in the tundish. The molten metal stream is poured into the atomization chamber using the gravity, where the molten metal stream gets disintegrated into spherical droplets due to jets of inert gases with very high kinetic energy. The spray thus formed gets accelerated towards the preformed substrate, cools down and solidifies partly as a result of high rate of heat transfer from the spray to the cold inert gas. The diameters of gas atomized droplets varies from $5\mu\text{m}$ to $500\mu\text{m}$. Later on the droplets impacts on to the substrate, merges and forms the deposit.

It was in 1960 in Swansea, Wales, by Singer and his colleagues when the first use of metal spray forming was used. In 1970s, spray forming was used as a substitute for conventional forming as production of done directly from the melt. The spray forming process for money-making was first used by a number of singer's young researchers and as a result of which they founded the company Osprey Metals in Neath, Wales. Hence sometimes spray forming process is also

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called as the Osprey process. Since then, application potentials of the spray forming process has ignited several researches and development works at universities and at various industries. In the late '80s Lavernia and Grant developed the liquid dynamic compaction (LDC) process which was similar to spray forming. LDC, Osprey process and spray forming are the generic names of similar or related processes.

2. Literature Review

“Professor Singer at the Swansea University first developed the idea of gas atomized spray forming in the 1970s in which a high pressure gas jet impinges on a stable melt stream to cause atomization.” “The resulting droplets are then collected on a target, which can be manipulated within the spray and used to form a near-dense billet of near-net shape Spray forming, also known as spray casting, spray deposition is a method of casting near net shape metal components with homogeneous microstructures via the deposition of semi-solid sprayed droplets onto a shaped substrate.” “In spray forming an alloy is melted, normally in an induction furnace, then the molten metal is slowly poured through a conical tundish into a small-bore ceramic nozzle. ”The molten metal exits the furnace as a thin free-falling stream and is broken up into droplets by an annular array of gas jets, and these droplets then proceed downwards, accelerated by the gas jets to impact onto a substrate.” “The process is arranged such that the droplets strike the substrate whilst in the semi-solid condition, this provides sufficient liquid fraction to 'stick' the solid fraction together. Deposition continues, gradually building up a spray formed billet of metal on the substrate.”

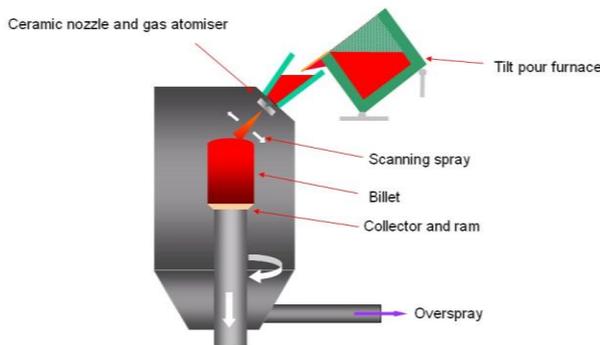


Fig 2.1: Layout of spray forming

3. Heat transfer equations

Heat transfer equations generally tells about variation of temperatures with respect to space co-ordinates (steady conditions) and variation of temperatures with respect to time (unsteady conditions). Heat transfer equation in slabs is given by:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{K} \rho C_p \frac{dT}{dt}$$

and heat transfer equation in cylinder is:

$$\rho C_p \frac{\partial T}{\partial t} = K \left[\frac{\partial^2 T}{\partial z^2} + \frac{1}{r} \frac{\partial}{\partial t} \left(r \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{d^2 T}{d\phi^2} \right]$$

And with the help of this equation we can know the temperature variations with respect to deposition time as show in fig below.

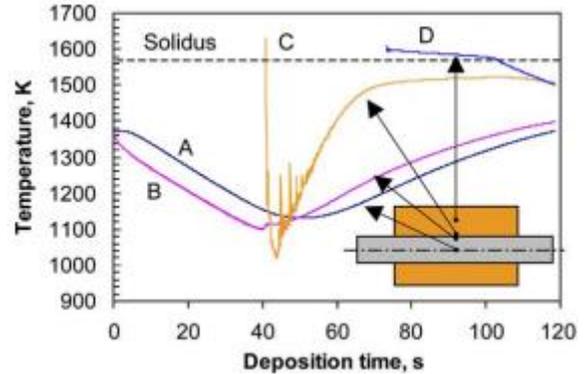


Fig 3.1: Thermal history at representative positions of tubular perform under the standard processing condition

4. Thermal profiles

“From the Chengsong Cui et. al the deposited material is cooled extensively and its temperature decreases rapidly.” “Following that, the temperature decreases slowly. The cooling rate of the deposited material at the base is higher than that in the center or in the top region.” “In the center of the deposit a mushy zone is formed, while the complete solid layers at the base and the top surface of the deposit promote cold porosity.” “The investigation of the effects of principal process parameters shows that the thermal profiles of a tubular deposit are sensitive to the mass input and enthalpy input from the spray.” “Preheating of the substrate in a furnace before spraying does not eliminate the base porosity due to extensive gas cooling.” The mass input and the enthalpy input from the spray of droplets to the preform are found to be the dominant influencing factors. The simulation results are in good agreement with the experimental results it can be seen from figure given below.

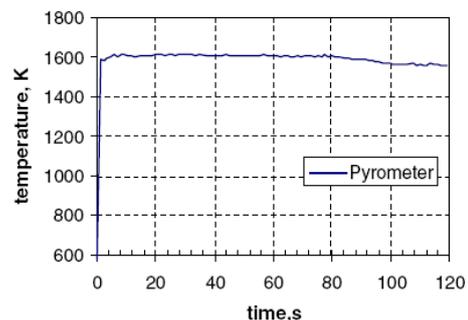


Fig.4.1: Deposit surface temperature measured by pyrometer under the standard processing condition

“From the Milan Ivosevic a, Richard A. Cairncross b etc. jets of high temperature and high velocity gases are used to melt and accelerate materials injected into the jet and propel them toward the surface to be coated.”
 “Upon impact at the surface, multiple hot particles deform, cool and consolidate to form a coating.”
 “Mathematical models have been developed to predict the particle transport and splatting on impact with a flat substrate during the High Velocity Oxy-Fuel (HVOF) combustion spraying of polymeric materials.”
 “The predicted shapes of deformed particles exhibited good qualitative agreement with experimentally observed splats including a characteristic “fried-egg” shape with large, nearly-hemispherical, core in the center of a thin disk.”

5. Thermal boundary conditions of deposits in spray forming

From literature Control of cooling during spraying of billets, chengsong chui,Udo fritsching, alwin Schulz: they told that porosity profiles and microstructures of spray of spray formed bearing steel are examined and evaluated.” “The investigation results show that the thermal boundary conditions of the deposits play important roles on the cooling and solidification behaviour of the deposits especially at the deposit periphery.” “Porosity in the bearing steel deposit can be reduced significant ally with the special cooling control system.” “It also told about the different value of heat transfer co-efficient. “it told that In the spray forming process the heat transfer of a deposit can be classified into several modes as show in fig below;(1) conductive heat transfer will take place inside the deposit (2) from deposit bottom to the substrate by convection and from deposits surface to gas by convection.” “So for producing homogeneous part the cooling and solidification conditions should be same for outer part and in the centre.”

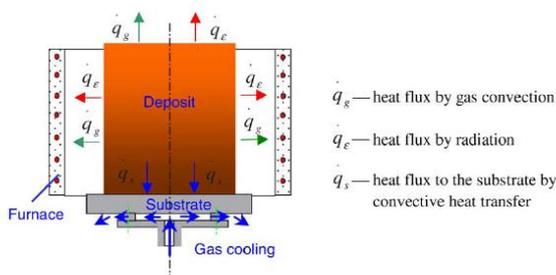


Fig.5.1: Heat transfer modes of a deposit and the cooling control system used in spray forming

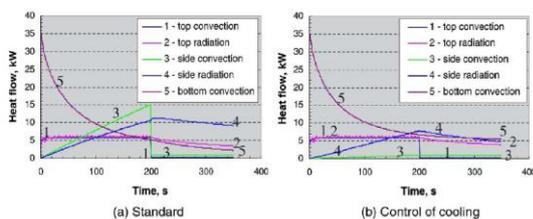


Fig.5.2: Heat flows at the surface of deposits in various modes and directions

6. Thermal history at various times and positions

“From the literature of chengsong cui,udo fritsching etc. for the manufacturing of bearing steels of low distortion potential steel billets were spray formed with respect to metallurgical homogeneity.”
 “Microstructure and properties of the billets produced under different thermal conditions were studied and evaluated.” “A heat transfer model of a growing billet was established to investigate the thermal profiles of the billet during spray forming.” “An apparent correlation between the cooling and solidification condition of the deposit and its deposit and metallurgical properties has disclosed by means of numerical simulation and experiment.”

“The fig below shown thermal history of various points within deposits.” “At the time of impingement deposit material cooled drastically and temp. decreases quickly. Cooling rate of the base material is high as compared to at the top and interior of the deposit.”

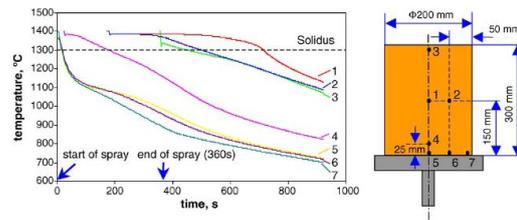


Fig6.1 Thermal history at different positions in spray formed billet

7. Mathematical Modelling

The numerical methods for solving differential equations are based on replacing the differential equations by algebraic equations. In the case of the popular finite difference method, this is done by replacing the derivatives by differences.

“A mathematical model is a description of a system using mathematical concepts and language. The process of developing a mathematical model is termed mathematical modelling.” “Mathematical models can take many forms, including but not limited to dynamical systems, generally make a governing equation and give the boundary conditions models, differential equations, or game theoretic models.” “These and other types of models can overlap, with a given model involving a variety of abstract structures.” “In general, mathematical models may include logical models, as far as logic is taken as a part of mathematics. In many cases, the quality of a scientific field depends on how well the mathematical models developed on the theoretical side agree with results of repeatable experiments.” “Lack of agreement between theoretical mathematical models and experimental measurements often leads to important advances as better theories are developed, here we make a governing equations and giving the boundary conditions. The numerical methods for solving differential equations are based on replacing the differential equations.

If slab made by spray forming for my modeling analysis.

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{k} \rho C_p \frac{dT}{dt}$$

Now I have to solve this equation with help of boundary conditions by using finite difference method.

8. Finite difference formulation of differential equation

“Therefore, replacing a differential time interval dt by a finite time interval of Δt = 1 day gave the same result, which leads us into believing that reasonably accurate results can be obtained by replacing differential quantities by sufficiently small differences.” “Next, we develop the finite difference formulation of heat conduction problems by replacing the derivatives in the differential equations by differences.” “In the following section we will do it using the energy balance method, which does not require any knowledge of differential equations.” “Derivatives are the building blocks of differential equations, and thus we first give a brief review of derivatives.” Consider a function f that depends on x, as shown in Figure below the first derivative of f(x) at a point is equivalent to the slope of a line tangent to the curve at that point and is defined as:

$$\frac{df(x)}{dx} = \lim_{\Delta x \rightarrow 0} \frac{\Delta f}{\Delta x} = \lim_{\Delta x \rightarrow 0} \frac{f(x+\Delta x) - f(x)}{\Delta x}$$

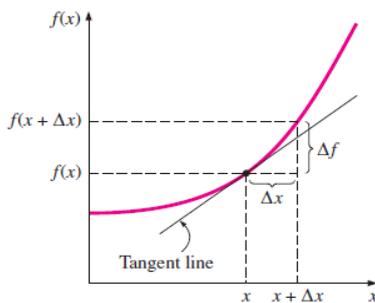


Fig.8.1 The derivative of a function at a point represents the slope of the function at that point

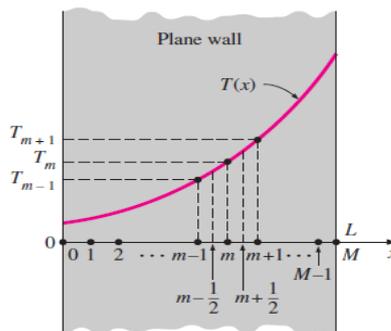


Fig.8.2: Schematic of the nodes and the nodal temperatures used in the development of the finite difference formulation of heat transfer in a plane wall

“Which is the ratio of the increment Δf of the function to the increment Δx of the independent variable as Δx → 0.” “If we don’t take the indicated limit, we will have the following approximate relation for the derivative.

$$\frac{df(x)}{dx} \cong \frac{d(x+\Delta x) - d(x)}{\Delta x}$$

“This approximate expression of the derivative in terms of differences is the finite difference form of the first derivative. The equation above can also be obtained by writing the Taylor series expansion of the function f about the point x, and neglecting all the terms in the expansion except the first two.”

$$f(x + \Delta x) = f(x) + \Delta x \frac{df(x)}{dx} + \frac{1}{2} \Delta x^2 \frac{d^2f(x)}{dx^2} + \dots$$

The first term neglected is proportional to Δx², and thus the error involved in each step of this approximation is also proportional to Δx². However, the commutative error involved after M steps in the direction of length L is proportional to Δx since MΔx² = (L/Δx) Δx² = LΔx. Therefore, the smaller the Δx, the smaller the error, and thus the more accurate the approximation. Now consider steady one-dimensional heat transfer in a plane wall of thickness L with heat generation. The wall is subdivided into M sections of equal thickness Δx= L/M in the x-direction, separated by planes passing through M + 1 points 0, 1, 2, . . . , m-1, m, m+1, . . . , M called nodes or nodal points, as shown in Figure. The x-coordinate of any point m is simply x_m=mΔx, and the temperature at that point is simply T(x_m)=T_m. The heat conduction equation involves the second derivatives of temperature with respect to the space variables, such as d²T/dx², and the finite difference formulation is based on replacing the second derivatives by appropriate differences. But we need to start the process with first derivatives. Using Eq, the first derivative of temperature dT/dx at the midpoints m-1/2 and m+1/2 of the sections surrounding the node m can be expressed as:

$$\left(\frac{dT}{dx}\right)_{m-\frac{1}{2}} \cong \frac{T_m - T_{m-1}}{\Delta x} \quad \text{and} \quad \left(\frac{dT}{dx}\right)_{m+\frac{1}{2}} \cong \frac{T_{m+1} - T_m}{\Delta x}$$

Noting that the second derivative is simply the derivative of the first derivative, the second derivative of temperature at node m can be expressed as

$$\left(\frac{d^2T}{dx^2}\right)_m \cong \frac{\left(\frac{dT}{dx}\right)_{m+\frac{1}{2}} - \left(\frac{dT}{dx}\right)_{m-\frac{1}{2}}}{\Delta x} = \frac{T_{m+1} - T_m}{\Delta x} - \frac{T_m - T_{m-1}}{\Delta x} = \frac{T_{m+1} - 2T_m + T_{m-1}}{\Delta x^2}$$

Which is the finite difference representation of the second derivative at a general internal node m. Note that the second derivative of temperature at a node m is expressed in terms of the temperatures at node m and its two neighbouring nodes.

Now for our analysis i.e. transient heat conduction. In transient problems, however, the temperatures change with time as well as position, and thus the finite

difference solution of transient problems requires discretization in time in addition to discretization in space, as shown in Figure. This is done by selecting a suitable time step Δt and solving for the unknown nodal temperatures repeatedly for each Δt until the solution at the desired time is obtained.

The formulation of transient heat conduction problems differs from that of steady ones in that the transient problems involve an additional term representing the change in the energy content of the medium with time. This additional term appears as a first derivative of temperature with respect to time in the differential equation, and as a change in the internal energy content during Δt in the energy balance formulation. The nodes and the volume elements in transient problems are selected as they are in the steady case, and, again assuming all heat transfer is into the element for convenience, the energy balance on a volume element during a time interval Δt can be expressed as:

(Heat transferred into the volume element from all of its surfaces during Δt) + (Heat generated within the volume element during Δt) = (the change in the energy content of volume element during Δt)

OR

$$\Delta t \times \sum_{\text{all sides}} \bar{Q} + \Delta t \times \dot{G}_{\text{element}} = \Delta E_{\text{element}}$$

Where the rate of heat transfer \bar{Q} normally consists of conduction terms for interior nodes, but may involve convection, heat flux, and radiation for boundary nodes.

Nothing that $\Delta E_{\text{element}} = mC\Delta t = \rho V_{\text{element}} C \Delta T$, where ρ is density and C is specific heat of the element. Dividing the earlier relation by Δt gives:

$$\sum_{\text{all sides}} \bar{Q} + \dot{G}_{\text{element}} = \frac{\Delta E_{\text{element}}}{\Delta t} = \rho V_{\text{element}} C \frac{\Delta T}{\Delta t}$$

Or for any node m in the medium and its volume element,

$$\sum_{\text{all sides}} \bar{Q} + \dot{G}_{\text{element}} = \rho V_{\text{element}} C \frac{T_{m+1} - T_m}{\Delta t}$$

Where T_m and T_{m+1} are the temperatures of node m at times $t_i = i\Delta t$ and $t_{i+1} = (i+1)\Delta t$, respectively, and $T_{m+1} - T_m$ represents the temperature change of the node during the time interval Δt between the time steps i and $i+1$. Note that the ratio $(T_{m+1} - T_m) / \Delta t$ is simply the finite difference approximation of the partial derivative $\Delta T / \Delta t$ that appears in the differential equations of transient problems. Therefore, we would obtain the same result for the finite difference formulation if we followed a strict mathematical approach instead of the energy balance approach used above.

Also note that the finite difference formulations of steady and transient problems differ by the single term on the right side of the equal sign, and the format of that term remains the same in all coordinate systems regardless of whether heat transfer is one-, two-, or three-dimensional. For the special case of $T_{m+1} = T_m$ (i.e., no change in temperature with time), the formulation reduces to that of steady case, as expected.

Conclusion

The described investigation is to identify the thermal conditions of metal particles impacting onto the pre-product during the spray forming process. The heat content and the solid fraction of these droplets has a significant influence on the overall cooling process of the product. In order to predict the thermal conditions of metal particles during the spray forming process, a numerical solidification model is described and a multiphase flow model is established to calculate droplet temperatures and solid fractions depending on main process parameters like gas-metal ratio [GMR] and the droplet's flight path inside the spray cone. The solidification model describes the different stages during phase change of a molten metal droplet, starting with an initial superheated temperature down to the temperature of the completely solidified droplets. The special properties of the materials are taken into account. Sample calculations using this model obtain a strict dependency of the droplet cooling behaviour on flight path of the droplets inside the spray cone and on gas to metal mass flow ratio [GMR].

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