HEAT TRANSFER MODELING OF METAL DEPOSITION EMPLOYING WELDING HEAT SOURCE

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ABSTRACT

The manufacturing of form-fit-function component rather then form-fit component is a major issue in Layered Manufacturing based Rapid Prototyping systems. As the deposition method, Gas Metal Arc welding (GMAW) has shown potential, for LM of metallic components, due to its inherent feature of high inter-layer and metallurgical bonding. Residual Stress induced warping is a major concern in a variety of LM processes, particularly those seeking to build parts directly without post processing steps. The temperature distribution and remelting depth plays an important role in controlling residual stresses and distortion. This paper presents a 3D finite element based thermal model of a novel welding based deposition process as applied to layered manufacturing. A Commercial finite element software ANSYS is coupled with a user programmed subroutine to implement the main welding features like Goldak Double Ellipsoidal Heat source, material addition and temperature dependent material properties. The model showed good agreement with experimental data. The results show that the process is not axis symmetric and a complete 3D model is required for accurate prediction of temperatures and deformation. The temperature distribution may be used for the prediction of residual stresses and distortions.

Keywords: *SFF, Welding, Layered Manufacturing, Inter-Pass Time*

INTRODUCTION

In mechanical engineering, rapid prototyping [1] is the process of building prototype objects to see whether a proposed design will be successful. Verifying "successful" designs has several aspects, including correct shapes, correct sizes, adequate strength, and others. The field of rapid prototyping has seen the recent introduction of automated systems that can convert a computer solid model into a three-dimensional artifact. These technologies have also been called "layered manufacturing" or "solid freeform fabrication" [2]. Layered manufacturing implies that these artifacts are built in two dimensional layers; this greatly simplifies these processes and enables their automation. Solid freeform fabrication implies that complex shapes are as easy to build when broken down into simple 2D shapes because there is no need of specific tooling.

The conventional RP techniques do not have the capability of directly producing fully functional parts, i.e. parts of high structural integrity (i.e. mainly metal parts) with excellent dimensional tolerances that could be used in operational systems. For the purpose of producing Form-Fit-Functional parts[3] and number of new methods are under development like Sintering, Brazing/Soldering and Shape Deposition Manufacturing (SDM)[4], but these methods all have there limitations like low density, addition of bonding materials etc, etc.

The principle of Gas Metal Arc Welding or GMAW have the promise to be used a metal deposition method[5] to produce parts with a high structural integrity and mechanical strength and in conjunction with CNC Machining it can be developed into a cost effective method for layered deposition manufacturing. The big draw back of using welding as the deposition process is the amount of heat that is pumped into the substrate material or the previous deposited layers which causes high temperature gradients which results in welding deformations like bowing, shrinkage, angular distortions and warping[6], more over the buildup of residual stresses is also of great concern but because of its better controllability of size and thermal state of the droplet and the thermal state of substrate by altering the welding parameters , the welding method is a more promising way to obtain high quality metal parts though Rapid Prototyping[7]. GMAW can also be used without machining to produce parts where dimensional tolerances are not very stringent but require high strength, like producing large parts like automobile engine casing [8]. The present research in use of GMAW as the deposition process for part buildup revolves around thermo-mechanical analysis of deposition process to reduce the buildup of Residual Stresses and deformations to control the dimensional tolerances.

The research in RP is limited mainly to the development of algorithms for optimized slicing procedures [9], determination of build up orientation [10] to reduce processing time and produce parts with required properties and automation of deposition process. Many layered manufacturing processes including weld based deposition and SDM are accompanied by the development of residual stresses. These stresses arise from the contraction of deposited material as it cools down [11]. These stresses cause distortions and de-laminations which are the main cause of failure. In order to predict and minimize these stresses and deformations correct estimation of temperature history is required. Research in thermal modeling of deposition process as applied to Layered Manufacturing is very limited. Microcasting, which is a discrete droplet based deposition process in SDM, is to some extent e.g. size of droplet, heat quantity and substrate re-melting is similar to welding. Droplet Level modeling of the Microcasting process has been performed by Chin [12], using a cylindrical droplet on a large cylindrical substrate to study the solidification behavior and buildup of residual stresses, this study was further extended to take into account successive droplets [13]. It was found that substrate preheating will decrease the cooling rate of the droplet and eventually will affect the build up of residual stress. a parametric study and effect of dissimilar materials was performed on a molten microcasted droplet by Zarzalejo [14], to come up with relevant processing parameters found in Microcasting like the droplet initial temperature and substrate pre-heating. The Numerical prediction reveal that the droplet initial temperature as found in Microcasting had a minimal effect on solidification, however, increasing the initial temperature will have a significant effect on re-melting depth. Substrate preheating will promote re-melting and decreases the cooling rates. The effect of dissimilar material combinations will significantly alter the cooling and re-melting behavior. A 1- Dimensional model of Microcasting droplet was developed by Amon [15], to predict the location of melting front. The numerical results were compared with Analytical solution and it was found that the analytical solution compares well with the initial phase of the solidification process. Nickel [16], developed a thermal model based on laser heating with no material addition, temperature independent material properties, to estimate the temperature history and subsequently stresses for different deposition patterns. The results shows difference in temperature history and stresses with various patterns but these results are not applicable to weld based deposition since the material addition will significantly alter the thermo-mechanical response and a welding heat source distribution is 3D and more diffused then a laser heat source.

The present research intends to develop a thermal model for weld based deposition using a moving Goldak Double Ellipsoidal heat source, temperature dependent material properties, time dependent material addition. The model can be used to predict accurately the fusion zone, temperatures and thermal effect of a moving heat source.

HEAT TRANSFER MODEL

A 3D thermal model is developed using a distributed moving heat source, referred as Goldak [17] double Ellipsoidal and material addition. The heat distribution within the moving heat source is given by Eq [1], while the applied heat distribution is shown in Figure [1].

$$q(x,y,z)=\frac{6.f_i.\sqrt{3}.Q}{a.b.c_i.\sqrt{(\pi.\pi)}}.e^{-3.(\frac{x}{a})^2}.e^{-3.(\frac{y}{b})^2}.e^{-3.(\frac{z}{c_i})^2} \qquad \text{Eq[1]}$$

$$Q=\eta.V.I$$

$$f_1+f_2=2$$

The heat transfer phenomena is modeled on the following assumptions

- Heat source overlapping for each pass is 50%
- The Convection present in the molten pool has been modeled by increasing the thermal conductivity to 100 W/m.K
- The conduction in the base plate is assumed one dimensional

Heat source and deposition parameters are given in Table [1]**.** The FE model consists of 25000, 3D Solid-70 element without mid side nodes. Mesh size is biased toward the deposition area. As the heat flow is dominantly in direction transverse to welding 18, therefore the mesh size is 1mm across the welding direction and 2 mm along the welding direction. The time step size is determined by dividing the length of heat source by welding speed.

The basic geometry of the model comprises of a rectangular substrate plate on which weld metal has been deposited to form a slab, as shown in Figure [2]. Initially a single layer has been modeled but the subroutine can be used to deposit multiple layers. The finite element model uses an 8 noded solid element with ability to model material addition feature during the analysis. A small element size is used in areas across the welding directions but a relatively large element size is used along the welding directions. A fine mesh is used in areas near the heat affected zone but the mesh becomes coarser in regions away from the welding zone. The temporal discretization depends upon the welding speed and the spatial mesh size. The finite element model is shown in Figure [2]. The deposition sequence is shown in Figure[3].

Table 1 Welding and Heat Source Parameters

S. No	Parameter	Value
1	a (mm)	5
2	b (mm)	4
3	C1 (mm)	5
4	C2 (mm)	15
5	Ff (mm)	0.5
6	Fr (mm)	1.5
7	Voltage (volts)	24
8	Current	232
9	Welding Speed (mm/sec)	6.25
10	Wire Feed (m/min)	8

The thermal boundary conditions comprise of combined convection and radiation from exposed surface of the substrate and filler material while the diffusion flux is defined at the interface of substrate and the base plate. The combined heat transfer coefficient for the top exposed surface of the substrate is temperature dependent and is calculated using the following relation

$$h_{eff}=h_{conv}+\varepsilon\sigma(T_s+T_\infty)(T_s{}^2+T_\infty{}^2) \qquad \text{Eq[2]}$$

The value of heff changes as the temperature of the surface is changed; the hconv is kept constant at a value of 5.3 W/m2 K, a typical value of free convection from a horizontal plate. The conduction to the base plate is modeled by applying an effective heat transfer coefficient at the base of substrate plate, based on the conductive thermal resistance of the base plate and contact resistance between the base plate and the substrate plate.

The thermal resistance based on conduction resistance and contact resistance Rc, as shown in Figure [4] across the base plate of thickness, t_b, is given as

$$R_b=R_c+\frac{t_b}{k} \qquad \text{Eq[3]}$$

The heat transfer coefficient for base plate conduction is calculated as;

$$h_b = \frac{1}{R_b} \qquad \text{Eq[4]}$$

The ambient temperature for both hb and heff is taken as 300 K.

Modeling Material Addition

Application of FEM to model continuous filler material addition requires special procedures. Two basic approaches are possible, namely, Method of Quiet Element and Inactive Element approach. In the quiet element approach the part of structure which has not been laid as yet is included in the initial computational model but these elements are made passive by assigning them with material properties so that they do not affect the rest of the model. They are given low stiffness i.e. low thermal conductivity, however these cannot be decreased too much since this will result in ill-conditioned matrix. These quiet elements will remain passive until the material properties are again changed to the actual values, and then they become part of the structure and thus simulate time dependent material addition. The second approach i.e. the inactive element method, the model is extended each time the material is added and they are not included as part of initial model. In this paper the quiet element approach is used and the stiffness scaling is done by a factor $10^{-6.}$

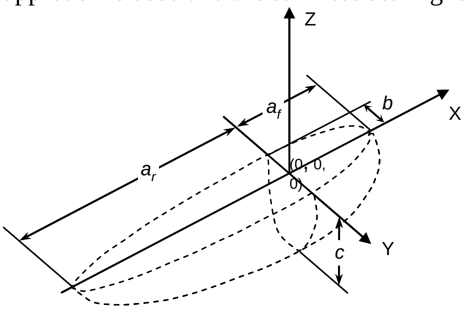

Figure 1: Goldak Heat Source Model

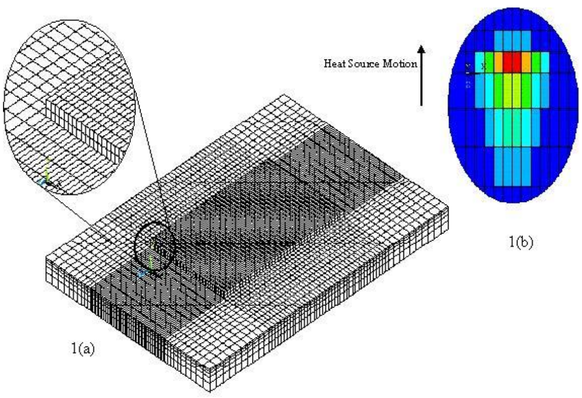

Figure 2: Heat Distribution

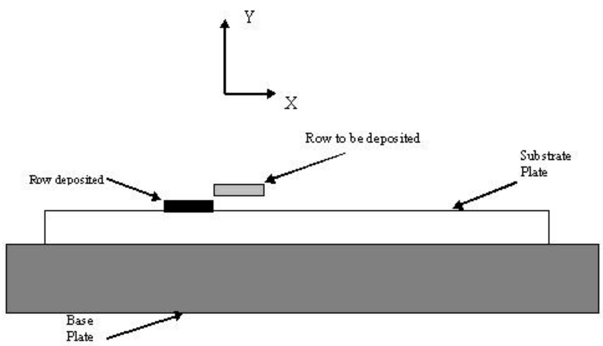

Figure 3: Deposition Sequence

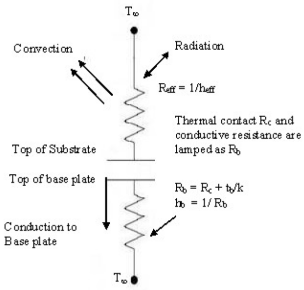

Figure 4: Conduction model for base plate

Experimental Setup

The result from 3D finite element model was compared against experimental data. The thermal model was verified by comparing the experimentally obtained fusion zone with numerically predicted fusion zone. The numerical and experimental temperature history was also compared. The temperature history was obtained by attaching a thermo-couple to point indicated as TC in Figure [5]. A 1.2 mm diameter mild steel welding wire, ER70S-6, is used to build a slab of 100 x 50 x 3.0 mm on the substrate using CO_2 as the shielding gas. The substrate plate was stress relieved and bolted, with M12 bolts, to base plates at four corners as shown in Figure [6] A long Raster deposition pattern is used along Z-direction .The deposition starts at the upper left corner of the area indicated as deposition area in Figure [6] and ends at the lower right corner.

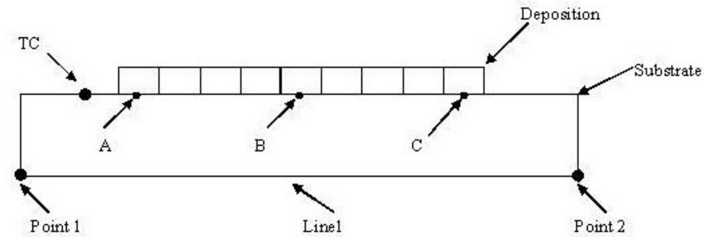

Figure 5: Result Points

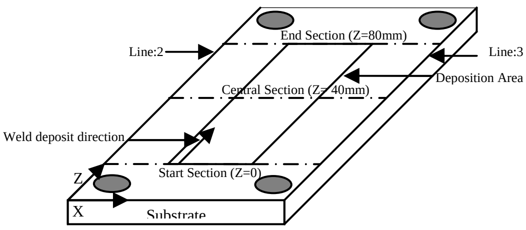

Figure 6: Deposition view

RESULTS AND DISCUSSION

The main aim of this work is to simulate the metal deposition using finite element method with specific application to rapid prototyping using gas metal arc welding. The validity of the proposed model depends on accurate prediction of temperatures and fusion zone.

For thermal model validation, numerically predicted fusion zone is compared with experimentally determined one. A bead on plate experiment with welding parameters similar to that used in the simulation was performed and the fusion zone was measured by cutting a sample from mid-length of the bead. . The sample was ground, polished and then etched with 2% nital. Position of liquidus isotherm for experimental and numerical weld bead is shown in Figure [7]. As the modeled size and the shape of the fusion zone are in conformity with the experimental results therefore the model can be used reliably for the prediction of remelting depth.

For further validity of the thermal model temperature history of the experimental and numerical study is also compared. A K-type thermocouple was spot welded at the position indicated as ‘TC’ in Figure [5] The temperature history up to first six passes is shown in Figure [8]. The predicted maximum temperature for “TC” matches the experimentally determined temperature and also the rise in temperature with each pass are reasonably similar.

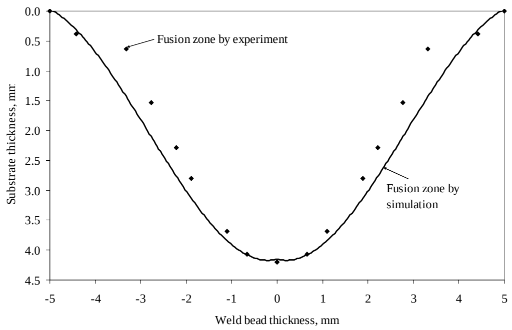

Figure 7: Comparison between numerical and experimental fusion zone

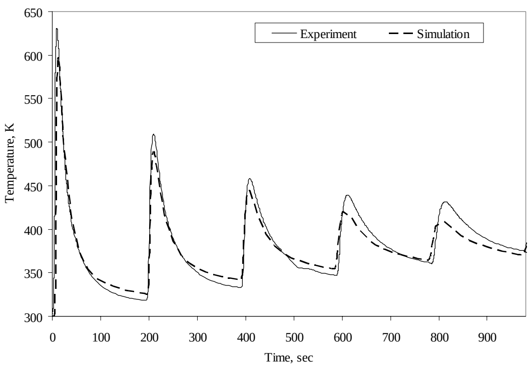

Figure 8: Temperature history verification

The Temperature history of nodes lying at the intersection of substrate top and center-line of a bead is shown in Figure [9]. The positions of these nodes are shown in Figure [5] as ‘A’, ‘B’ and ‘C’. The peak temperature for each point is same but the time at which this peak occurs is dissimilar. It is observed that when the heat source is close to any of the point under consideration, the temperature of that point is relatively higher therefore it can be concluded that the magnitude of thermal cycling is not symmetric but depends upon the relative position of the heat source. The deposition and substrate are geometrically symmetric but the temperature history shows that any assumption of thermal symmetry during deposition modeling is not realistic as temperature differences between the nodes are observed. This is in disagreement with the assumptions made in Nickel **Error! Reference source not found.**, where raster pattern is modeled as lying between two symmetry planes. It is also observed that at the start of each pass, due to interpass cooling, the temperatures of all the nodes under considerations are almost same. Interpass cooling thus plays a major role in controlling the operational substrate temperatures which in turn will control the surface quality of the product.

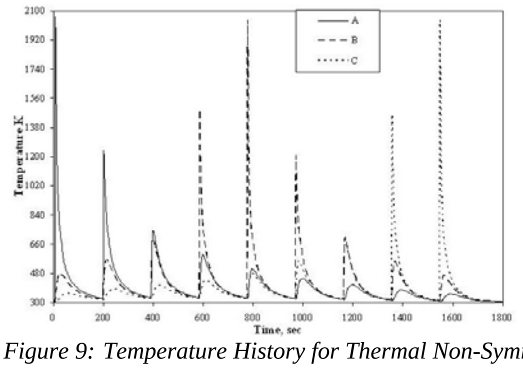

Figure 9: Temperature History for Thermal Non-Symmetry

In order to ascertain the thermal non symmetry of the process the temperature history of two nodes represented as point 1 and point 2 are presented in Figure [10]. The locations of these nodes are shown in Figure [5].

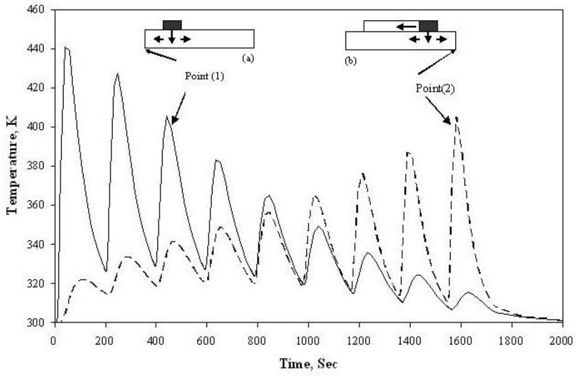

Figure 10: Thermal Non-Symmetry

The two nodes experience same number of thermal cycling equal to the number of passes but the node ‘point 1’ acquire higher temperature then the node ‘point 2’. This difference in temperatures can be attributed to decrease in thermal conductive resistance as material is added; this is presented schematically in Figure [10]. When the first row is deposited the conduction in transverse direction takes place along path’s as shown by arrows, however when the last row is deposited the previous material added results in an additional transverse conduction path thus reducing the amount of heat reaching point 2. The above arguments are enough to establish that the process is not thermally symmetric therefore any assumption of thermal symmetry is not valid. Figure[11] shows the preheat available to the substrate after the inter-pass cooling(3 minutes cooling between consecutive passes) and also demonstrate that for first passes the difference of temperatures between deposition start and end is comparatively large around 30~40 degrees but after the fifth pass the difference comes down to 10 degrees. This almost uniform preheat will definitely result in reduction of residual stresses and distortion, moreover altering the deposition sequence can also have the beneficial effect of uniform preheat.

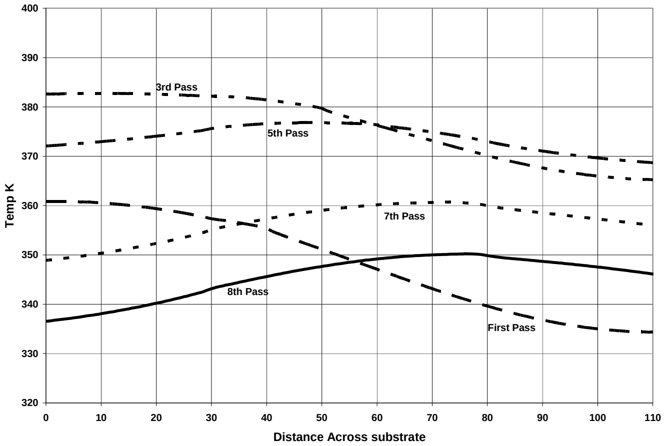

Figure 11: substrate Preheat after inter-pass cooling

CONCLUSIONS

A finite element model was developed to predict the thermal behaviour associated with molten metal deposition, as applied to welding based layered manufacturing. The results show that the model can accurately predict the re-melting depth and transient temperature distribution. The thermal results have shown that the process is not thermally symmetric because of the moving heat source as well the presence of additional weld metal. The finding is in contrast to more commonly used thermally symmetric assumptions.

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NOMENCLATURE

a.	=	Width of Heat Source (mm), along x axis
b.	=	Depth of Heat Source (mm)
c_1	=	Length of Frontal Ellipsoidal(mm)
c_2	=	Length of Rear Ellipsoidal(mm)
E	=	Young's Modulus (GPa)
f_1	=	Fraction of Heat Deposited in Frontal Ellipsoidal
f_2	=	Fraction of Heat Deposited in Rear Ellipsoidal
h_{efff}	=	Effective Heat Transfer Co-efficient (W/m^2 K)
hconv	=	Co-efficient of Free Convection (W/m^2 K)
h_b	=	Effective Heat Transfer Coefficient of Base Plate Conduction (W/ m^2 K)
I	=	Welding Current (Amp)
K	=	Stiffness of Base plate (N/m)
K	=	Thermal conductivity of Base plate (W/ m K)
n	=	no of contact elements
Q	=	Total Arc Heat (W)
q^*	=	Heat Density (W/m^3)
R	=	Thermal Resistance(K/W)
t_s	=	Thickness of Substrate plate(mm)
t_b	=	Thickness of Base plate(mm)
t_d	=	Thickness of Deposition(mm)
T	=	Temperature (K)
h	=	heat transfer coefficient (W.m^{-2}.K^{-1})
k	=	thermal conductivity (W.m^{-1}.K^{-1})