THE ANNALS "DUNĂREA DE JOS" UNIVERSITY OF GALAŢI
FASCICLE V, TECHOLOLOGIES IN MECANICAL ENGINEERING, ISSN 1221-4566
2004

Study of Remelting Processes During the Droplet-Based Solid Freeform Fabrication

PhD. Maria Neagu, eng. Aurora Dinicuţă, eng. Emil Banea
University "Dunărea de Jos" of Galaţi

Abstract

This paper presents the study of the droplet based solid freeform fabrication process. Its main objective is the analysis of the substrate remelting as well as the remelting of the deposited material that occurs for high droplet superheat. The influence of the droplet superheat and cooling conditions as well as the deposition frequency on the substrate and the deposited material remelting depth is also analyze

Keywords:*Droplet-based Solid Freeform Fabrication, remelting.*

1. Introduction

Droplet-based Solid Freeform Fabrication (SFF) [1] is a new emerging technology developed for manufacturing solid parts layer by layer using a stream of droplets. This manufacturing process is not unique in the landscape of research activity developed in the world, research that use droplets for creating high precision and complex shape parts.

From the same family, we can enumerate: the Solid Freeform Fabrication (SFF), Shape Deposition Manufacturing (SDM), Spray Forming. The difference between them are related to the way of obtaining the droplets, the droplets dimension and the manufacturing precision. In the droplet-based SFF process the droplets are obtained from capillary break-up (the diameter $\phi \sim 100\mu m$) followed by electrostatic deflection; in SDM method [2, 3] a feedstock wire is melted over a workpiece using a plasma torch ($\phi = 1 \div 10\mu m$) while in Spray Forming method, a spray of molten metal is formed by atomising a fluid column of molten metal (ϕ varies and the precision is reduced).

The droplet-based SFF method is the most accurate method of them, as the droplet stream has high angular and stream dispersion stability [1]. Another important aspect is the remelted zone of the deposited material. A constant thickness of this zone is important for the micro-homogeneity and macro-stability of the workpiece.

This paper is using a one-dimensional model of the process in order to study the influence of the droplets superheating temperature on the substrate remelting as well as the influence of the droplets superheating temperature, cooling conditions and the deposition frequency on the deposited material remelting depth.

2. Analytical and numerical model

2.1 Analytical and numerical model of substrate remelting

The one-dimensional model developed by this work is considering a constant temperature substrate and a deposited melted droplet. Depending on the initial temperature of the droplet, there is the possibility of the substrate to remelt first on a certain depth (Fig.1a), a process that is followed by the substrate solidification and ,subsequently, the droplet solidification (Fig.1b). The position of the solidification front (s) is negative for the substrate remelting and positive for the droplet solidification case.

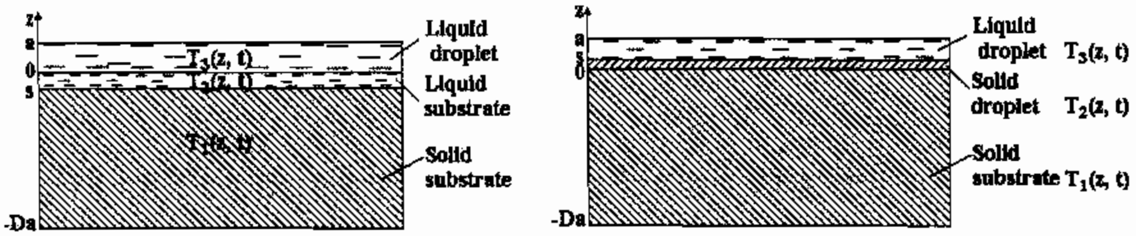
The analytical model is considering the one-dimensional heat transfer equation:

$$\frac{\partial^2 T_i}{\partial z^2} = \frac{1}{\alpha_i}\frac{\partial T_i}{\partial t} \qquad (1)$$

where the subscript is (throughout this paper) i =1÷3 corresponding to the material domains presented in Fig.1(a); T is the temperature field, t is time and α is the corresponding thermal diffussivity. The boundary conditions necessary for solving the three temperature fields are:

$$T = T_i \text{ at z=-Da;} \qquad (2)$$

$$T_1 = T_2 = T_{m\_sub} \text{ at z=s;} \qquad (3)$$



(a) (b)

Fig. 1: Physical domain during substrate remelting (a) and droplet solidification (b).

$$-k_2\frac{\partial T_2}{\partial z} = -k_3\frac{\partial T_3}{\partial z} \text{ at } z=0; \qquad (4)$$

$$-k_3\frac{\partial T_3}{\partial z} = h\left(T_3 - T_\infty\right) \text{ at } z=a, \qquad (5)$$

where a is the droplet thickness , s is the position of the phase transition front; T_{m_sub} is the melting temperature of the substrate, h is the heat transfer coefficient, k is the thermal conductivity and T_∞ is the ambient temperature.

For Fig.1(b), the heat transfer equation corresponding to the three domains is (1), while the boundary conditions necessary are:

$$T = T_i \text{ at } z=\text{-Da}; \qquad (6)$$

$$-k_1\frac{\partial T_1}{\partial z} = k_2\frac{\partial T_2}{\partial z} \text{ at } z=0; \qquad (7)$$

$$T_2 = T_3 = T_m \text{ at } z=s; \qquad (8)$$

$$-k_3\frac{\partial T_3}{\partial z} = h\left(T_3 - T_\infty\right) \text{ at } z=a, \qquad (9)$$

where T_m is the droplet melting temperature.

In order to obtain a general solution and clear results, the following non-dimensional variables are considered: $\theta = \left(T - T_m\right)/\left(T_m - T_{sub}\right)$, for the temperature; $Z = z/a$, for the length and $\tau = t\alpha_{2s}/a^2$, for time; T_{sub} is the substrate initial temperature and α_{2s} is the solid droplet thermal diffussivity.

The computational domains are presented by Fig. 2(a) and Fig.2(b). The corresponding non-dimensional thermal fields obey the non-dimensional heat transfer equations:

$$\frac{\partial^2\theta_i}{\partial Z^2} = \frac{1}{\tilde{\alpha}_i}\frac{\partial\theta}{\partial\tau}; \qquad (10)$$

and the corresponding boundary conditions:

$$\theta = -1 \text{ at } Z=\text{-D}; \qquad (11)$$

$$-\tilde{k}_i\frac{\partial\theta_i}{\partial Z} = -\tilde{k}_j\frac{\partial\theta_j}{\partial Z} \text{ at } Z=0; \qquad (12)$$

for i=1,2 and j=3,2;

$$\theta_1 = \theta_2 = \theta_{m\_sub} \text{ at } Z=S; \text{ Fig.2(a)}; \qquad (13)$$

$$\theta_2 = \theta_3 = 0 \text{ at } Z=S; \text{ for Fig. 2(b)}; \qquad (13')$$

$$\frac{\partial\theta_3}{\partial Z} + Bi\cdot\left(\theta_3 - \theta_\infty\right) = 0 \text{ at } Z=1, \qquad (14)$$

where $\tilde{\alpha}_i = \alpha_i/\alpha_{2s}$, S=s/a, $\tilde{k}_i = k_i/k_{2s}$ and the Biot number $Bi = ha/k_{2s}$, where k_{2s} is the solid droplet thermal conductivity and $\theta_{m\_sub} = \left(T_{m\_sub} - T_m\right)/\left(T_m - T_{sub}\right)$. The velocity of the solidification front for Fig.2(a) can be found from (15):

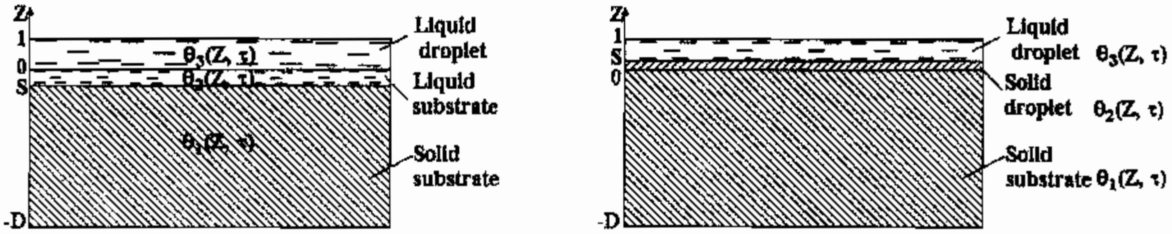
$$k_1\frac{\partial\theta_1}{\partial Z} - k_2\frac{\partial\theta_2}{\partial Z} = \tilde{L}_{sub}\frac{dS}{d\tau} \qquad (15)$$

where $\tilde{L} = L_{sub}/C_{p2s}/\left(T_m - T_{sub}\right)$, L_{sub} is the substrate latent heat of fusion, C_{p2s} is the droplet heat capacity. The velocity of the solidification front for Fig.2(b) can be found from (16):

$$k_2\frac{\partial\theta_2}{\partial Z} - k_3\frac{\partial\theta_3}{\partial Z} = \tilde{L}\frac{dS}{d\tau} \qquad (16)$$

where $\tilde{L} = L/C_{p2s}/\left(T_m - T_{sub}\right)$, L is the droplet latent heat of fusion.

The numerical model used by this work is the finite difference method. Centered finite differences were used for the computational domain while forward and backward finite differences were used for the boundary points.



(a) (b)

Fig. 2: Computational domain for the non-dimensional problem during the substrate remelting (a) and droplet solidification (b).

Each region of the computational domain was divided using 100 points on the Z direction while the time step $\Delta\tau = 10^{-3}$. A Crank-Nicholson scheme was used for its stability properties.

2.2. Analytical and numerical model of droplets remelting

The model developed by this work is considering a constant temperature substrate and subsequent deposited droplets, the deposition frequency being constant. When a droplet is deposited, its solidification process begin, but sometimes, depending on the process parameters, the previous deposited material remelts on a thickness X. Figure 3(a) is presenting the substrate, the solid deposited material and the liquid deposited material at a certain deposition moment.

The analytical model is also considering the one-dimensional heat transfer equation (1), where the subscript is i = 1÷3 corresponding to the substrate, solid or liquid deposited material. The boundary conditions necessary for solving the three temperature fields are:

$$T = T_i \text{ at } z=-Da; \tag{17}$$

$$-k_1 \frac{\partial T_1}{\partial z} = k_2 \frac{\partial T_2}{\partial z} \text{ at } z=0; \tag{18}$$

$$T_2 = T_3 = T_m \text{ at } z=s; \tag{19}$$

$$-k_3 \frac{\partial T_3}{\partial z} = h(T_3 - T_\infty) \text{ at } z=(M=1)a, \tag{20}$$

where M is the number of the previous deposited droplets. Using the non-dimensional variables defined previously, the computational domain presented by Fig. 3(b) obeys the heat transfer equations (10) and the following boundary conditions:

$$\theta = -1 \text{ at } Z=-D; \tag{21}$$

$$-\tilde{k}_1 \frac{\partial \theta_1}{\partial Z} = -\tilde{k}_2 \frac{\partial \theta_2}{\partial Z} \text{ at } Z=0; \tag{22}$$

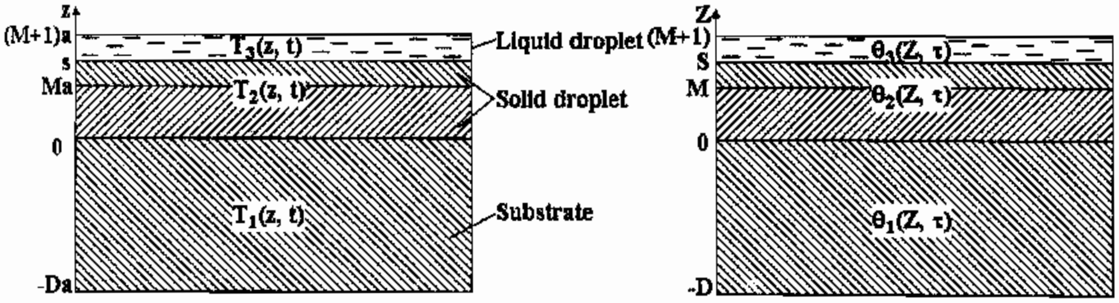
$$\theta_2 = \theta_3 = 0 \text{ at } Z=S; \tag{23}$$

$$\frac{\partial \theta_3}{\partial Z} + Bi \cdot (\theta_3 - \theta_\infty) = 0 \text{ at } Z=M+1, \tag{24}$$

The velocity of the solidification front can be found from (25):

$$-k_3 \frac{\partial \theta_3}{\partial Z} + k_2 \frac{\partial \theta_2}{\partial Z} = \tilde{L} \frac{dS}{d\tau}, \tag{25}$$

Between two consecutive depositions, there were considered only two regions with the boundary conditions (21), (22) and (24). The numerical model used by this work is the finite difference method. Centered finite differences were used for the computational domain while forward and backward finite differences were used for the boundary points. Each region of the computational domain was divided using 100 points on the Z direction while the time step $\Delta\tau = 10^{-5}$. Using this values, the stability criteria is satisfied.



(a) (b)

Fig. 3: Physical (a) and computational (a) domain during droplets remelting.

3. Results and discussion

Figure 4 is presenting the solidification front position as a function of time for different superheating droplet temperatures and Biot number Bi=1. As we can clearly see, the substrate remelting occurs for higher values of droplet superheating. Previous works [2, 3] underlined the fact that higher superheat can be

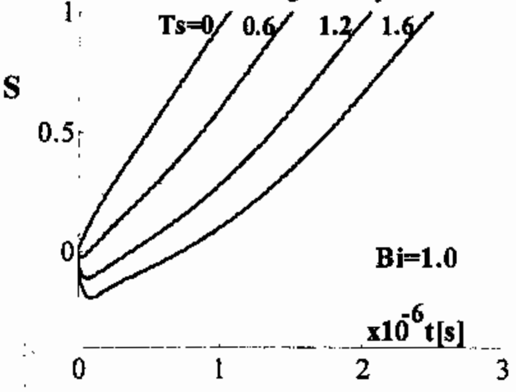


Fig. 4. S-t variation for different superheating temperatures.

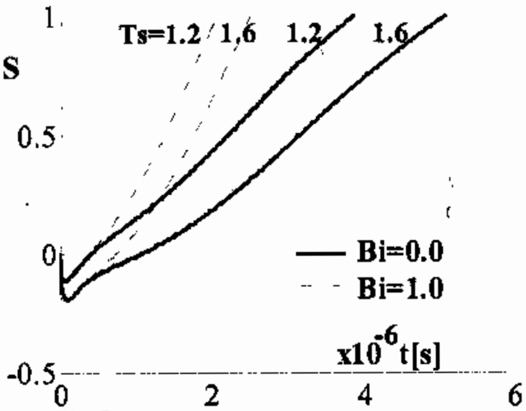


Fig.5. S-t variation for different cooling conditions.

obtained not only through high initial temperatures of the incoming droplet but also through smaller initial substrate temperature. Sometimes, undercooling of the substrate is considered.

The influence of the cooling conditions is analysed by the results presented by Fig.5. The remelting depth does not depend significantly on the cooling conditions, except the substrate solidification time: it is smaller when Bi number si greater.

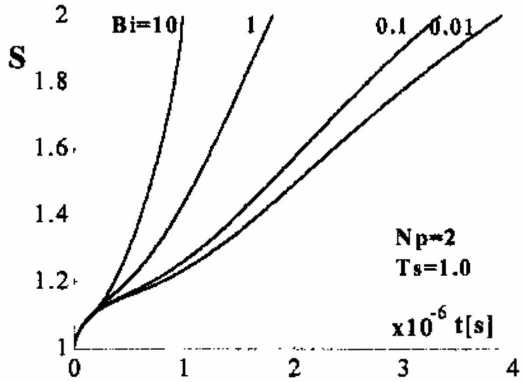


Fig.6. S-t variation for different cooling conditions.

Figure 6 is presenting the solid thickness when a second droplet is deposited on a previous droplet. When the cooling conditions are better, the Biot number is greater, the solidification time is smaller.

Depending on the superheat (T_s) of the incoming droplet the solid material remelts and the remelt thickness (X) increases as T_s increases (Fig. 7): if Biot number increases, the remelt thickness decreases.

The remelt thickness increases during the deposition process as the number of deposited droplets (Np) increases (Fig. 8). Good cooling conditions are inducing an important change of the remelted region and the difference is higher as the number of droplets increases. Taking into consideration the cooling conditions becomes a crucial parameter for the structure and the properties of the workpiece. When the deposition frequency is doubled $(\Delta t = 112\mu s)$ (Fig.9), the influence of the cooling conditions are not significant and the remelt depth differences diminish.

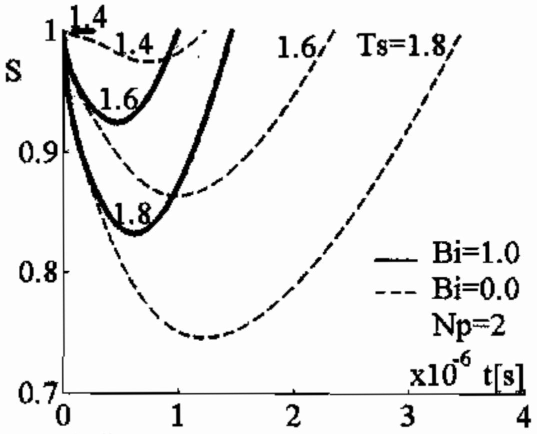


Fig.7. S-t variation for different droplet Superheats.

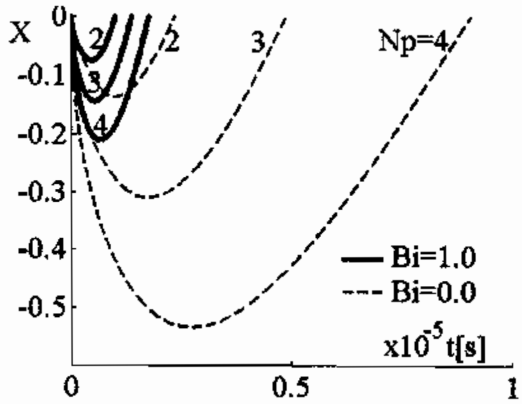


Fig. 8. X-t variation (Δt=56μ). T_s=1.0.

An equal remelted material thickness (X), during the whole process, is an ideal goal for constant properties deposited layer. Figure 10 is analysing the time variation of the droplet superheat necessary for obtaining a constant

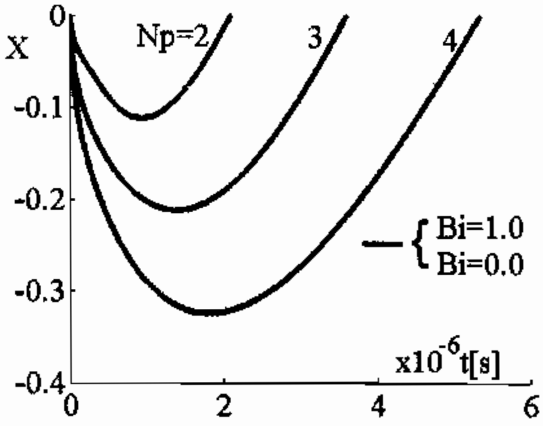


Fig. 9. X-t variation (Δt=112μ). T_s=1.0.

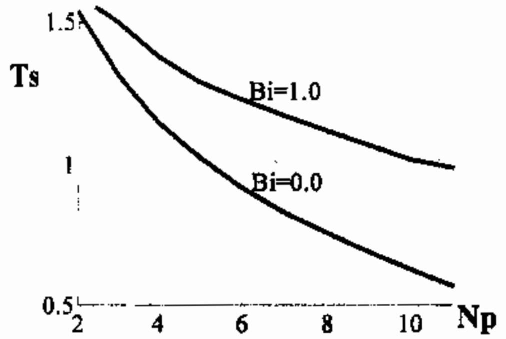


Fig. 10. Ts-Np variation for X=0.1 and Δt=56μs.

remelt thickness and it shows that the incoming droplet temperature must decreases in time. This reduction is less important if the cooling conditions are better and the process is much more uniform.

4. Conclusions

This paper is analyzing the substrate as well as the deposited material remelting during the droplet based Solid Freeform Fabrication process. The one-dimensional model shows that the substrate remelting occurs only for certain droplet superheats. The Biot number (the cooling conditions) do not influence the substrate remelting depth. It influence only the substrate melting/solidification time.

The temperature superheat as well as the cooling conditions are influencying the droplet solidification process as well as the remelting depth of the deposited material:

- the solidification time is smaller for higher Biot number (better cooling conditions);
- for certain initial droplet superheat, the deposited material remelting occurs. The remelting depth is higher for higher superheats;
- the deposited material remelting depth depends on the number of droplets deposited previously. It increases as the droplet number is higher. This variation disappears for smaller deposition frequencies;
- in order to mentain a constant variation depth during successive droplet deposition, the incoming droplet superheat must decreases.

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Étude des Processus de Refonte pendant la Fabrication Pleine de Freeform -Basée par Gouttelette

Résumé

Cet article présente l'étude du processus plein de fabrication de freeform basé par gouttelette. Son objectif principal est l'analyse du substrat refondant aussi bien que la refonte du matériel déposé qui se produit pour la gouttelette élevée surchauffent. L'influence de la gouttelette surchauffent et des états de refroidissement comme la fréquence de dépôt sur le substrat et la profondeur de refonte du matériel déposée est analysent également.

Studiul Procesului de Retopire în Timpul Fabricării Formelor Complexe bazată pe Picături

Rezumat

Această lucrare prezintă studiul procesului fabricării formelor complexe bazat pe picături. Obiectivul principal al lucrării este analiza topirii substratului ca si al retopirii materialului depus, procese ce apar la anumite supraincălziri iniţiale ale picăturilor. Infleunţa supraîncălzirii picăturilor, a condiţiilor de răcire la fel ca şi a frecvenţei de depunere asupra proceselor de topire/retopire este analizată.