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Numerical Modeling of the Sintering Process

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ABSTRACT

This work is the analysis of the height variation of a two-dimensional porous layer (the layer is made of two materials: Nickel and Carbon steel) during the sintering process. The melting is a direct contact melting process (the classical method) and the nominal dimensions of the workpiece impose a two-dimensional analysis. The problem is solved in a non-dimensional manner for the generality of the solution and the clarity of the results. The work presents the evolution of the layer height during the sintering process as well as the influence of cooling and preheating conditions on these dimensions.
***Keywords**: sintering, melting, porous material, two-dimensional, numerical modeling.*

1. Introduction

The sintering process is becoming more and more important in the field of the non-conventional manufacturing technologies. Between the sintering methods, the direct contact melting method (the classical method) [1, 2] and the selective laser sintering method [3, 4] are leader methods in this field.

Experimental [1, 2, 3] and numerical [1, 3, 4, 5] works are analyzing these processes and the workpiece parameters. The evolution of the workpiece height is one of the parameters determined by the shrinkage of the porous material, shrinkage that appears during the sintering process. If [3] and [4] are treating the selective laser sintering method using experimental and analytical tools, [1] and [2] are analyzing analytically and numerically the direct contact melting process of a porous layer. The analysis of the direct contact melting process is one-dimensional. It uses the enthalpy method and the shrinkage of the porous layer height is not taken into consideration in the numerical modeling while the experimental results are presenting it as an observation that is not sustained by the numerical model. The influence of the process parameters (cooling conditions, e.a.) is not considered either.

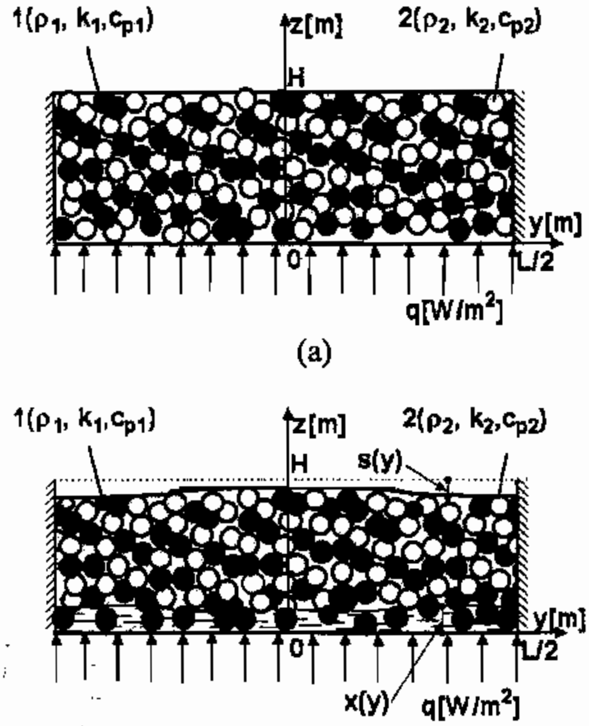
This study is analyzing the direct contact melting of a two component packed porous layer (Nickel/Carbon Steel) heated from bellow by a constant heat flux and cooled by convection at the superior boundary, while the side boundaries are isolated. During the sintering process, the low melting point material is changing its phase, it becomes liquid and it flows through the high melting point material. This last one, cannot sustain the whole structure and move downwards influencing not only the workpiece height but also the whole heat transfer process. Using a finite difference method for a two-dimensional model, this work is taking into consideration not only the influence of the porous layer shrinkage due to the moving downward of the non-melting material, but also the influence of the convection process of the liquid bellow the phase transition front. Its influence on the deformation of the porous layer upper boundary is analyzed. The influence of the cooling conditions and the preheating conditions is also taken into consideration in this study.

2. Mathematical formulation

2.1 Governing equations

Figure 1 presents the layer of the two powder materials, the high melting point material (1) and the low melting point material (2) as well as their physical properties: density (ρ), thermal conductivity (k) and specific heat (c_p). The layer is heated from bellow by a constant heat flux, q[W/m2], and cooled by convection from above as in the sintering process. The heat flux is applied such that only the low melting point material melts (Fig.1b).

While the melt moves through the high melting point material due to capillary forces and gravity, the phase transition boundary whose position is denoted by x(y) (Fig.1b) is moving upwards as the sintering process



(b)

Fig. 1. Porous layer at the beginning (a) and during (b) the sintering process.

continues. The high melting point material cannot sustain anymore the whole structure and moves downward influencing the heat transfer process. Consequently, the porous layer is diminishing its height (H) continuously with a value s(y), its evolution being one of the main objectives of this paper.

In order to solve numerically this problem, three conservation equations will be written for the mass, momentum and energy:

- the "continuity" equation is written for the high melting point material (1) and for the low melting point material (2) in the solid (s) and liquid (l) phase:

$$\frac{\partial \varphi_i}{\partial t} + \nabla \cdot \left(\varphi_i v_i\right) = M \,, \qquad (1)$$

where i=1, 2s, 2l (these subscripts will be used throughout the paper) and M=0, $-\dot{m}/\rho_{2l}$ or $\dot{m}/\rho_{2l}$, respectively; φ is the volume fraction; $\dot{m}$ is the mass production rate of the liquid obtained during the melting process; t is time; v_{2l} is the liquid velocity with two components: u_l for the y direction and v_l for the z direction.

- the flow of the liquid is respecting Darcy's law:

$$v_{2l} - w_l = -\frac{KK_{rl}}{\varphi_l \mu}\left(-\nabla P_c + \rho_{2l} g\right), \qquad (2)$$

where: K is the permeability of the porous layer, K_{rl} is the relative permeability, P_c is the capillary pressure, w_l is the velocity of the solid matrix:

$$w_l = \begin{cases} 0, \; z > x \\ -(1-\varepsilon)\dfrac{\partial x}{\partial t}, \; z \le x \end{cases} \qquad (3)$$

- the energy conservation equation (4):

$$\frac{\partial}{\partial t}\left\{\left[\varphi_l c_l + \left(\varphi_{2l} + \varphi_{2s}\right)c_{2l}\right]T\right\} + \nabla \cdot \left(\varphi_{2l} v_{2l} c_{2l} T\right) + \frac{\partial}{\partial z}\left[w_l\left(\varphi_l c_l + \varphi_{2s} c_{2s}\right)T\right] = \nabla \cdot \left(k \nabla T\right) - \left\{\frac{\partial}{\partial t}\left[\left(\varphi_{2l} + \varphi_{2s}\right)S\right] + \nabla \cdot \left(\varphi_{2l} v_{2l} S\right) + \frac{\partial}{\partial z}\left(\varphi_{2s} w_l S\right)\right\} \qquad (4)$$

where c_1, c_2, S and k and kl are defined elsewhere [3]; T is the temperature; h_{sl} is the latent heat of melting and the effective thermal conductivity k_{eff} is defined elsewhere [4]. The definition of c, S and k are considering that the melting process is taking place in a temperature range ΔT.

The boundary conditions used for solving the energy conservation equation (4) are:

$$-k\frac{\partial T}{\partial z} = q \text{ at z=0;} \qquad (5)$$

$$-k\frac{\partial T}{\partial z} = h\left(T - T_\infty\right) \text{ at z=H,} \qquad (6)$$

where T_∞ is the ambient temperature and h is the heat transfer coefficient.

The system of equations (1), (2) and (4) has to be solved simultaneously in order to know completely the temperature (T), velocity (u_l, v_l, w_l) and volume fraction (φ) fields.

2.2 Non-dimensional formulation

In order to obtain a general solution and clear results, the following non-dimensional variables are defined [3]:

$$\theta = \frac{T - T_m}{T_m - T_i} \qquad (7)$$

for the temperature, such that θ = 1 is the melting point and θ = 0 is the initial temperature;

$$\tau = \frac{\alpha_1 t}{H^2} \quad (8)$$

for time;

$$(Z,Y) = \frac{(z,y)}{H} \quad (9)$$

for height and length, such that $Z \in [0,1]$ at the beginning of the sintering process.

The other non-dimensional variables become:

- $U = uH/\alpha_1$, $V = vH/\alpha_1$, for the fluid velocity field in the y and z directions;
- $W = wH/\alpha_1$ for the velocity of the solid matrix;
- $C = c/c_1$, $K = k/k_1$ for the heat capacity and thermal conductivity;
- $S = s/H$ for the height reduction of the porous layer;
- $X = x/H$ for the melting front position and
- $\tilde{L} = L/H$ for the workpiece length.

Figure 2 presents the non-dimensional computational domain. The governing equations (1), (2) and (4) become:

$$\frac{\partial \varphi_{2l}}{\partial \tau} + \nabla \cdot (\varphi_{2l} V_{2l}) = \frac{\alpha_1 M}{H^2}, \quad (10)$$

$$V_{2l} - W_s = \frac{\varepsilon Ma \psi_e^3}{(1-\varepsilon)\psi\sqrt{180}} \nabla P_c + \frac{\varepsilon^2 Ma Bo \psi_e^3}{180(1-\varepsilon)^2 \psi} \quad (11)$$

$$\frac{\partial}{\partial t}\{CT\} + \nabla \cdot (\varphi_{2l} V_{2l} C_{2l} \theta) + \frac{\partial}{\partial z}[W1(\varphi_1 C_1 + \varphi_{2s} C_{2s})\theta] = \nabla \cdot (K \nabla \theta) - \left\{\frac{\partial}{\partial t}[(\varphi_{2l} + \varphi_{2s})S] + \nabla \cdot (\varphi_{2l} V_{2l} S) + \frac{\partial}{\partial z}(\varphi_{2s} W_1 S)\right\} \quad (12)$$

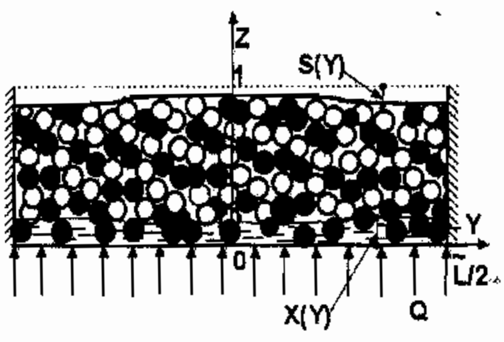


Fig. 2. Computational domain for the non-dimensional problem.

The boundary conditions (5) and (6) become:

$$-\frac{\partial \theta}{\partial Z} = Q \text{ at } Z=0; \quad (13)$$

$$\frac{\partial \theta}{\partial Z} + Bi(\theta - \theta_\infty) = 0 \text{ at } Z=1, \quad (14)$$

where ε, the voids volume fraction, d and γ_m^0 are presented by Table 1; α- the thermal diffusivity; g- the gravitational acceleration; Bi is the Biot number, $Bi = hH/k$, Ma- the Marangoni number $Ma = \gamma_m^0 d/(\alpha_1 \mu)$, Bo- the Bond number $Bo = \rho_{2l} g H d/(\gamma_m^0)$, $Q = qH/k/(T_m - T_i)$, the heat flux.

2.3 Numerical method

The numerical method used is the finite difference analysis. The grid has 25 points in the Z direction, 24 points in the Y direction and the time step is $t=10^{-2}$ seconds. The implicit method scheme is used with centered finite differences in the entire domain while forward and backward finite differences are used at the boundaries.

Table1

Process parameters.

Physical properties	Symbol	Value
Density [Kg/m^3]	ρ_1	2500
	ρ_{2l}	1250
	ρ_{2s}	1261.4
Thermal conductivity [W/m/K]	K_1	0.74
	K_{2s}	0.39
	K_{2l}	0.13
Latent heat of melting [J/Kg]	h_{sl}	87204.17
Melting temperature	T_m	1271
Viscosity [kg/sm]	μ	5.473 x10^{-3}
Surface tension al T_m [N/m]	γ_m^0	1.207
Average grains dimension [μm]	d	90
Layer height [m]	H	0.02
Initial volume fractions	ε	0.4
	φ_1	0.36
	φ_{2s}	0.24

Table 1 presents the constant parameters considered in the process. A square cavity was considered, such that $\tilde{L} = 1$, Marangoni number Ma=2084 and Bond number Bo=0,142.

3. Results and discussions

Figure 3 presents the non-dimensional height variation as a function of time for the material

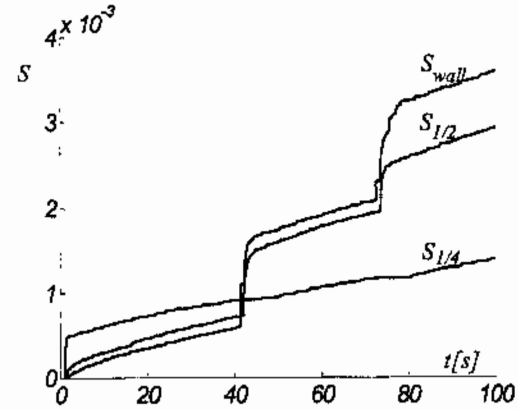


Fig. 3. Workpiece height reduction as a function of time. Bi=0.1

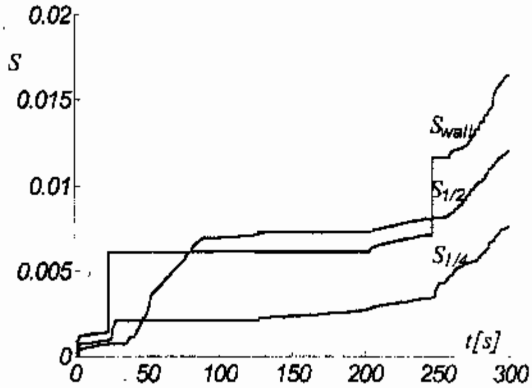


Fig. 5. Layer height reduction as a function of time. $Bi=10^{-2}$.

situated near the wall (S_wall), at the center of the workpiece ($S_{1/2}$) and at a quarter to the wall ($S_{1/4}$). The results are showing that S_wall has maximum values during the sintering process and $S_{1/4}$ has minimum values. The difference of the height variation along the length (Y) of the workpiece can be explained by the natural convection process of the liquid situated bellow the melting front.

This convection process is similar to the fluid convection in the same cavity. The liquid convection is, also, responsible for the melting front variation as a function of time. Its shape and evolution is a proof of this mechanism. As we can notice, different points along the Y axis are moving downward differently such that the upper surface is not a plane one.

More than that, the height variation is not smooth. On the contrary, the variation is taking place in steps as it was noticed before, experimentally by Pak and Plumb [1]. This model is proving analytically the steps-like evolution of a porous layer height during the sintering process having as point of start the conservation laws for mass, momentum and energy.

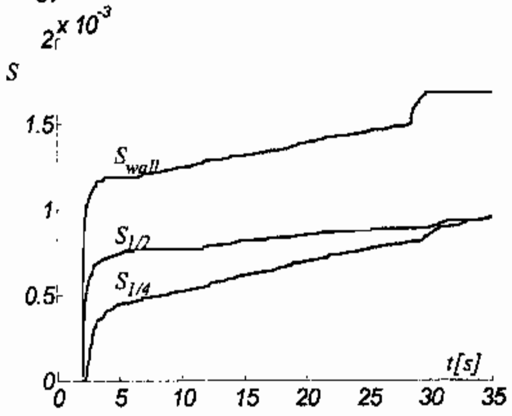


Fig. 4. Layer height reduction as a function of time.Bi=1.

The Biot number is giving us a measure of the cooling process taking place at the upper boundary of the cavity, a higher Biot number meaning better cooling conditions. Its influence on the porous layer height variation is analyzed in Fig.4 and Fig.5. Figure 4 is presenting non-dimensional height (S) variation as a function of time for Bi=1, while Fig. 5 presents the same variation for $Bi=10^{-2}$. As we can notice, a smaller Biot number, a poor cooling at the upper boundary is inducing smaller number of steps with higher amplitudes. For a higher Biot number, the amplitudes of the steps decrease and the variation of the layer height is a smoother one.

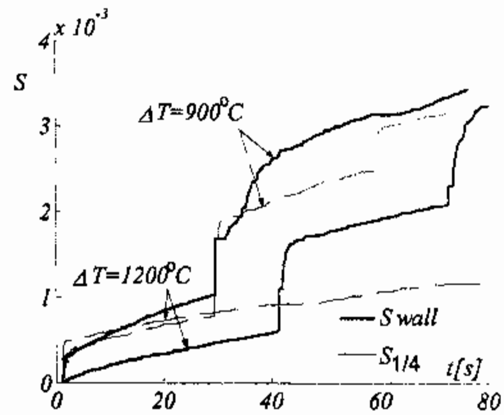


Fig. 6. Layer height reduction as a function of pre-heating conditions.

Another process parameter that is influencing the layer height variation is the preheating conditions. Figure 6 is presenting the height reduction variation for two different preheating conditions: T_m-T_i=1200°C and T_m-T_i= 900°C, where T_i is the initial temperature of the porous material. As we can clearly notice from Fig. 6, a higher difference between the melting and the initial temperature, T_m-T_i, is leading to higher differences of the upper boundary of the workpiece.

4. Conclusions

This paper is presenting the analysis of the direct contact melting sintering of a two materials (Nickel and Carbon steel) porous layer. A non-dimensional analysis is developed for the two-dimensional case using finite differences method.

The height of the porous layer is decreasing during the sintering process, and that is not a continuous or a smooth process. The decrease of the layer height is taking place in steps-like processes, aspects noticed experimentally by other researchers in previous works [1]. This model is proving this variation analytically using the conservation laws.

This paper is analyzing the variation of the height on the process parameters through the preheating conditions and cooling conditions. While the amplitude of these steps are higher as the Biot number increases at the upper boundary, the sintering process is presenting a much more continuous and smooth variation of the porous layer height if the cooling conditions are better. It was noticed that high preheating temperatures are improving the quality of the workpiece by decreasing the deformations at the upper boundary.

The factors that are determining a smooth variation of the porous layer height and smaller deformations at the upper boundary have important practical applications. The steps-like variation of the porous layer height during sintering should be analyzed by future works for a better understanding of the process conditions that are influencing it and for the experimental verification of its mechanisms.

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Model Numérique du Processus d'Agglomération

Résumé

Ce travail est l'analyse de la variation de taille d'une couche poreuse bidimensionnelle (la couche est faite de deux matériaux : nickel et acier) pendant le processus d'agglomération. C' est un procédé d'agglomration par contact direct (la méthode classique) et les dimensions nominales de l'objet imposent une analyse bidimensionnelle. Le problème est résolu d'une façon non-dimensionnelle pour la généralité de la solution et la clarté des résultats. Le travail présente l'évolution de la taille de couche pendant le processus d'agglomération aussi bien que l'influence de refroidir et de préchauffer des conditions sur ces dimensions.

Modelare Numerică a Procesului de Sinterizare

Rezumat

Această lucrare este o analiză a variaţiei inălţimii unui strat poros bi-dimensional format din două materiale (Nichel şi oţel carbon) în timpul procesului de sinterizare. Procesul este unul clasic de sinterizare iar dimensiunile piesei impun o tratare bi-dimensională a problemei. Aeasta este rezolvată într-o manieră bi-dimensională pentru generalizatea soluţiei şi claritatea rezultatelor . Lucrare prezintă evoluţia înălţimii stratului de material în timpul procesului de sinterizare precum şi influenţa condiţiilor de răcire şi preîncălzire asupra acestor dimensiuni.