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The Dimensions of a Packed Porous Layer During Sintering

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ABSTRACT

This work is an analysis of a height variation of a porous layer (he layer is made of two materials, Nickel and Carbon steel) during sintering process. The melting is a direct contact melting process (the classical method) and the nominal dimensions of the workpiece allows a uni-dimensional analysis. The problem is solved in a non-dimensional manner for the generality of the solution presented here. The work presents, also, the dependence of the sintered porous layer height as a function of the material properties (material porosity, e.a.) and the working conditions (energy consumption, pre-heating conditions, cooling conditions).

***Keywords**: sintering, porous material.*

1. Introduction

The sintered workpieces are becoming more and more important in the field of the non-conventional worked pieces. 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] works are analyzing the process and workpiece parameters. The height evolution of the workpiece is one of these parameters knowing the shrinkage of the porous material, shrinkage that appears during the sintering process.

This study is taking into consideration the two component packed porous layer (Nickel/Carbon Steel) heated from bellow by a constant heat flux and cooled by convection at the superior boundary. Even if the combination of the two materials has been studied before for a selective laser sintering process [3], a direct contact melting procedure is considered this time. This paper is considering not only the influence of the capillary pressure but also the velocity of the high melting point material matrix in the heat transfer process.

2. Mathematical formulation

Figure 1 presents the layer of the two powder materials, the high melting point material (1, black grains) and the low melting point material (2, white grains) 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).

The liquid moves through the high melting point material due to capillary forces and gravity. The melting boundary, whose position is denoted by x (Fig.1b) is moving upwards as 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 y. y is increasing during sintering till a maximum value. Its evolution will be the main objective 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:

$$\frac{\partial \varphi_i}{\partial t} + \frac{\partial}{\partial z}(\varphi_i v_i) = M \ , \qquad (1)$$

where i=1,2s,2l (these subscripts will be used throughout the paper) and M=0, $-\frac{\dot{m}}{\rho_{21}}$ or $\frac{\dot{m}}{\rho_{21}}$, respectively; φ is the volume fraction; $\dot{m}$ is the

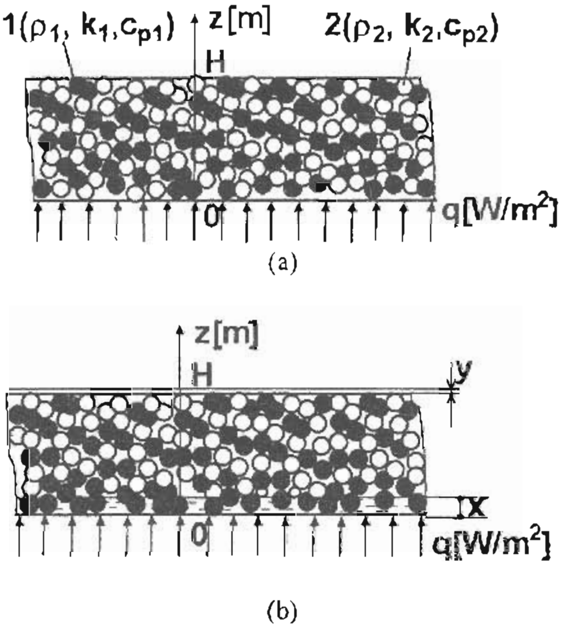

Fig. 1 Porous layer at the beginning (a) and during (b) the sintering process.

mass production rate of the liquid obtained during the melting process; t is time; v is the liquid velocity.

The volume fractions satisfy the equation:

$$\varepsilon + \varphi_{2s} + \varphi_l = 1, \qquad (2)$$

where ε is the total volume of voids, including the volume of gas and liquid relative to the total volume of the porous layer. A constant porosity assumption is used in this work.

- the flow of the liquids is considered in only one direction, and the Darcy's low becomes:

$$v_{2l} - w_l = -\frac{KK_{rl}}{\varphi_l \mu}\left(\frac{\partial P_c}{\partial x} + \rho_{2l} g\right) \qquad (3)$$

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

$$w_l = \begin{cases} 0, & z < x \\ -(1-\varepsilon)\dfrac{\partial x}{\partial t}, & z \geq x \end{cases} \qquad (4)$$

The definition and the calculation of these properties is presented elsewhere [3,4].

- the energy conservation equation (5) where the heat capacity

$$c_l = \rho_l c_{pl} \qquad (6)$$

$$\frac{\partial}{\partial t}\{[\varphi_l c_l + (\varphi_{2l} + \varphi_{2s})c_{2l}]T\} + \frac{\partial}{\partial z}(\varphi_{2l} v_{2l} c_{2l} T) + \frac{\partial}{\partial z}[w_l(\varphi_l c_l + \varphi_{2s} c_{2s})T] = \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)$$
$$-\left\{\frac{\partial}{\partial t}[(\varphi_{2l} + \varphi_{2s})S] + \frac{\partial}{\partial z}(\varphi_{2l} v_{2l} S) + \frac{\partial}{\partial z}(\varphi_{2s} w_l S)\right\} \qquad (5)$$

$$c_2 = \begin{cases} \rho_{2l} c_{p2l}, & T < T_m - \Delta T \\ \rho_{2l} c_{p2l} + \dfrac{\rho_{2l} h_{sl}}{2\Delta T}, & T_m - \Delta T < T < T_m + \Delta T \\ \rho_{2l} c_{p2l}, & T > T_m + \Delta T \end{cases} \qquad (7)$$

$$S = \begin{cases} 0, & T < T_m - \Delta T \\ \rho_{2l} h_{sl}/2, & T_m - \Delta T < T < T_m + \Delta T \\ \rho_{2l} h_{sl}, & T > T_m + \Delta T \end{cases} \qquad (8)$$

$$k = \begin{cases} k_{eff}, & T < T_m - \Delta T \\ k_{eff} + \dfrac{k_l - k_{eff}}{2\Delta T}, & T_m - \Delta T < T < T_m + \Delta T \\ k_l, & T > T_m + \Delta T \end{cases} \qquad (9)$$

where $k_l = (\varphi_{21} + \varphi_{2s})k_{21} + \varphi_l k_l$;

T is the temperature; h_{sl} is the latent heat of melting and 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 are:

$$-k\frac{\partial T}{\partial z} = q \text{ at } z=0; \qquad (10)$$

$$-k\frac{\partial T}{\partial z} = h(T - T_\infty) \text{ at } z=H, \qquad (11)$$

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

The system of equations (1), (3), (5) has to be solved simultaneously in order to know completely the temperature (T), velocity (v, w) and volume fraction (φ) fields.

3. Non-dimensional formulation

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

$\theta = (T - T_m)/(T_m - T_i)$ for the temperature, such that $\theta = 1$ is the melting point and $\theta = 0$ is the initial temperature; $\tau = \alpha_l t / H^2$ for time;

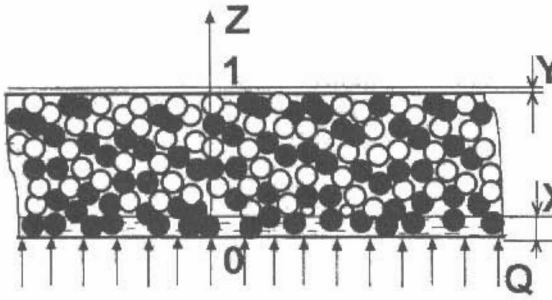

Fig. 2 Computational domain for the non-dimensional problem.

$Z = z / H$ for length, such that $Z \in [0,1]$ at the beginning of the sintering process (H was considered 20mm throughout this paper); $V = vH/\alpha_1$, $W = wH/\alpha_1$ for the velocity field; $C = c/c_1$, $K = k/k_1$ for the heat capacity and thermal conductivity; $Y = y/H$ for the height reduction of the porous layer and $X = x/H$ for the melting front position.

The computational domain of the non-dimensional problem is presented by Fig. 2.

The equations (1), (3) and (5) become:

$$\frac{\partial \varphi_i}{\partial \tau} + \frac{\partial}{\partial z}(\varphi_i V_i) = \frac{\alpha_l M}{H^2}, \qquad (12)$$

$$V_l - W_s = \frac{\varepsilon Ma \psi_e^3}{(1-\varepsilon)\psi\sqrt{180}} \frac{\partial P_c}{\partial z} + \frac{\varepsilon^2 MaBo \psi_e^3}{180(1-\varepsilon)^2 \psi} \qquad (13)$$

$$\frac{\partial}{\partial t}\{CT\} + \frac{\partial}{\partial z}(\varphi_{2l} V_{2l} C_{2l} \theta) + \frac{\partial}{\partial z}[W1(\varphi_l C_l + \varphi_{2s} C_{2s})\theta] = \frac{\partial}{\partial z}\left(K \frac{\partial \theta}{\partial z}\right) - \left\{\frac{\partial}{\partial t}[(\varphi_{2l} + \varphi_{2s})S] + \frac{\partial}{\partial z}(\varphi_{2l} V_{2l} S) + \frac{\partial}{\partial z}(\varphi_{2s} W_l S)\right\} \qquad (14)$$

The boundary conditions(10÷11) become:

$$-\frac{\partial \theta}{\partial Z} = Q \ at\ Z=0; \qquad (15)$$

$$\frac{\partial \theta}{\partial z} + Bi(\theta - \theta_\infty) = 0 \ at\ Z=1, \qquad (16)$$

where Bi is the Biot number, $Bi = hH/k$, Ma is the Marangoni number $Ma = \frac{\gamma_m^0 d}{\alpha_1 \mu}$, Bo is the Bond number, $Bo = \frac{\rho_{2l} g H d}{\gamma_m^0}$, $Q = \frac{qH}{k(T_m - T_i)}$;

μ is the viscosity; α is the thermal diffusivity; g is the gravitational acceleration; d is the average grain dimension and γ_m^0 is the liquid surface tension at the melting temperature.

A finite difference analysis is used with 150 points in the z direction and a time step of $t=10^{-1}$ seconds. The constant parameters considered in the process are presented by Table 1.

Table1. Process parameters.

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	5.473×10^{-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

4. Results and discussions

Figure 3 is presenting the time variation of the layer height reduction. As it can be seen, this

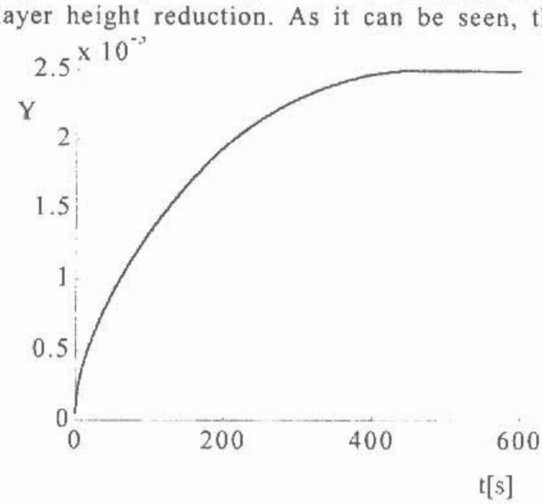

Fig. 3 Layer height reduction as a function of time.

reduction has a maximum value beyond which the layer height does not reduce anymore if the same working conditions are mentained.

The dependence of layer height reduction depends strongly on the power input, as Fig.4 is presenting.

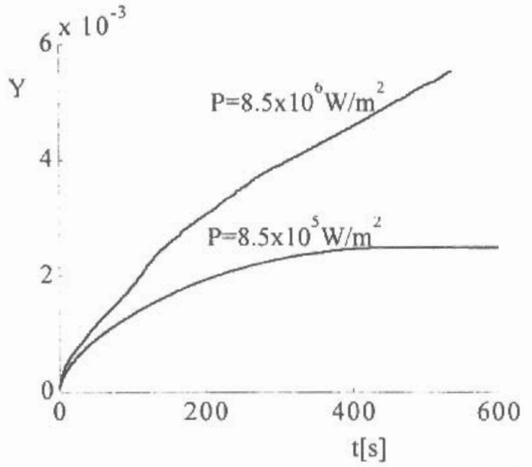

Fig. 4 Layer height reduction as a function of power input.

Figure 5 is analyzing the layer height reduction and its dependence on the initial preheating of the workpiece. Two situations are presented: without preheating (T_m-T_i=1200°C) and preheating at 700°C (T_m-T_i=500°C). The results are indicating that the preheating

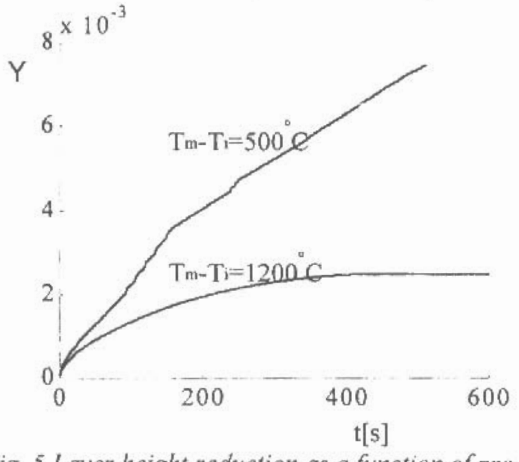

Fig. 5 Layer height reduction as a function of pre-heating conditions.

conditions play a crucial role in the layer height reduction.

Another process parameter that is influencing the workpiece is the cooling conditions at the upper boundary. Figure 6 is presenting Y variation as a function of time for Bi=10^{-4} and Bi=1.0. The value Bi=1 is indicating a good thermal contact of the porous layer and the environment and , as Fig.6 shows,

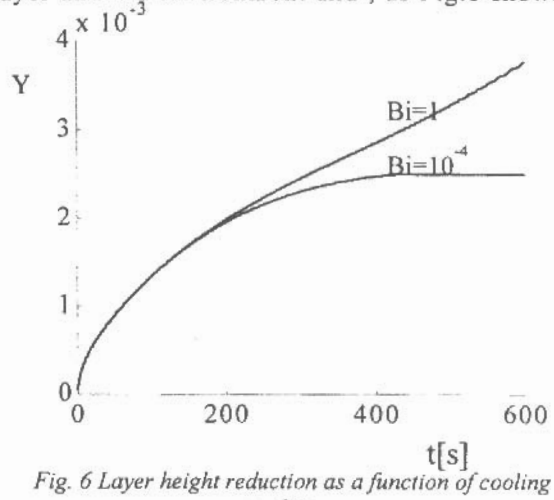

Fig. 6 Layer height reduction as a function of cooling conditions.

its influence is significant.

5. Conclusions

This paper is presenting the analysis of the direct contact melting process that is taking place during sintering. A non-dimensional analysis is developed for the one dimensional case having as object of study a pair of two materials Nickel and Carbon steel (1.5%C).

The reduction of the porous layer is increasing during sintering till a maximum value. Its level depends on the process parameters through the power input (Fig. 4), in an expected manner, preheating conditions (Fig.5) and cooling conditions (Fig.6).

A good thermal contact of the material with the environment and a preheating treatment is inducing a higher reduction of the porous layer height during sintering process.

References

[1] **Pak, J., Plumb, O.A.**, *Melting in a Two-Component Packed Bed*, Journal of Heat Transfer, 1997, (2), 553-559.

[2] **Kearns, D.A., Plumb, O.A.**, *Direct Contact Melting of a Packed Bed*, Journal of Heat Transfer, 1995, (2), 452-456.

[3] **Zhang, Y., Faghri, A.**, Buckley, C.W., Bergman, T.L., *Three-Dimensional Sintering of Two-Component Metal Powders With Stationary and Moving Laser Beams*. Journal of Heat Transfer, 2000, (1), 150-158.

[4] **Zhang, Y., Faghri, A.**, *Melting and Resolidification of a Subcooled Mixed Powder Bed With Moving Gaussian Heat Source*. Journal of Heat Transfer, 1998, (4), 883-890.

Dimensiunile Unui Strat Poros
In Timpul Sinterizarii

Rezumat

Acestă lucrare este o analiză a variației inălțimii unui strat poros alcătuit din două materiale, Nichel și oțel, în timpul procesului de sinterizare. Topirea are loc prin contact direct (metoda clasică) iar dimensiunile nominale ale piesei considerate permite o analiză unidimensională a piesei. Problema este rezolvată adimensional pentru a oferi generalitate soluției prezentate. Lucrarea prezintă, de asemenea, dependența variației înălțimii stratului poros sinterizat funcție de proprietățile de material (porozitatea materialului, etc.) și de condițiile de lucru (energia consumată, preîncălzire).

Les Dimensions D'une Couche Poreuse
Pendant L'agglomération

Résumé

Ce travail est une analyse d'une variation de taille d'un couche poreuse (il est fait en deux matériaux, stell et nickel) pendant le processus d'agglomération. La fonte est un procédé de fonte de contact direct (la méthode classique) et les dimensions nominales de l'objet permet une analyse unidimensionnelle. Le problème est résolu d'une façon non-dimensionnelle pour la généralité de la solution présentée ici. Le travail présente, aussi, la dépendance du couche poreuse en fonction des propriétés matérielles (porosité, e.a.) et les conditions de travail (consommation d'énergie, préchauffant états, états de refroidissement).