A CFD Approach for Prediction of Unintended Porosities in Aluminum Syntactic Foam: A Preliminary Study

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A CFD Approach for Prediction of Unintended Porosities in Aluminum Syntactic Foam: A Preliminary Study

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ABSTRACT

Aluminum Syntactic Foam (ASF) is a material with great potential in applications related to lightweight structures and structural damping. However, experimental investigations in literature report that the infiltration process to fabricate ASF often results in incomplete infiltration. Published studies on modeling the infiltration process are mainly based on a porous media/permeability approach. This approach focuses on the global porosity of ASF rather than local unintended porosity, since it does not include the infiltration pattern around the individual spherical particles. This paper reports a numerical approach that enables for the simulation of the flow through the porous corridors of the preform. The numerical approach is established in the commercial software FLOW-3D and consists of a finite volume based computational fluid dynamics solver and a volume of fluid algorithm which together calculates the pressure, velocity and free surface of the aluminum. The results of the numerical model illustrate that this method has great potential of predicting unintended porosities in ASF and thereby optimizing the parameters involved in the infiltration process.

INTRODUCTION

Aluminum Syntactic Foam (ASF) is a material where an aluminum based metal matrix is embedded with spherical particles, e.g. cenospheres or glass microspheres. It has an increasing range of applications in many fields, e.g. the automobile, railway and aerospace industries, due to low relative density, low coefficient of thermal expansion and high damping insulation of vibration, sound and heat [1-3].

Among many fabricating processes of Aluminum Syntactic Foam, the infiltration process is the most common manufacturing method, where the molten aluminum is infiltrated into a preform consists of spherical particles under an external pressure [4-7]. However, previously published researches report that the infiltration process has many defects, such as incomplete infiltration, which can reduce the quality of ASF.

Numerical modeling method can provide information of the flow and thermal condition during the infiltration process, and then suggest optimized infiltration process parameters in order to reduce the experimental work. Previous papers [8-10] on modeling the infiltration process mainly consider the mass, momentum, and energy-balance equations together with Darcy's law which describes the flow of the fluid inside a porous media. However, this approach primarily focuses on the global unintended porosity of ASF rather than local unintended porosity. Besides, in order to utilize this approach, the permeability of the preform and the drainage curve which represents the degree of saturation as a function of pressure are both known. It requires a series of testing infiltration experiments to measure these parameters.

In this paper, a Computational Fluid Dynamics (CFD) based numerical approach is presented. It simulates the flow condition of the molten aluminum though the porous preform, and shows the potential to predict the unintended porosities at the end of the infiltration process. However, the big obstacle for the CFD approach is that the size of the preform is usually around 10cm, while the size of the spherical particles is between 50 to 300μm. The size of the control volumes is at least the same as the size of the spherical particles, and it results in a heavy calculation. Therefore, the purpose of this paper is to evaluate the possibility for this CFD approach to simulate the infiltration process within a reasonable time.

First, the CFD model together with a description of the porous preform is presented. Afterwards, the simulation results are shown and compared with a similar case from literature [8] using a porous media/permeability approach.

NUMERICAL MODEL

Governing Equations

The flow of the molten aluminum through the porous preform during the infiltration process is a highly non-linear problem. Two main physical phenomena, the flow and solidification of the molten aluminum, are involved in the infiltration process. In this preliminary study, the thermal calculations are not considered, only the flow of the molten aluminum is calculated. In addition, the molten aluminum is considered as an incompressible Newtonian fluid.

For global Newtonian flow, the mass continuity equation and the momentum equations are solved, as given in Eqn. 1 and 2, respectively.

$$\nabla u = 0 \quad (1)$$

$$\rho\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\nabla p + \mu \nabla^2 u \quad (2)$$

where u is the velocity of the molten metal, ρ is the density, t is the time, p is the pressure. Note that no gravitational force, surface tension or pore pressure are considered in this study.

CFD Solver

The commercial software FLOW-3D is used to calculate the incompressible Newtonian flow of the molten aluminum [11]. FLOW-3D is a CFD software analyzing various physical flow processes. FLOW-3D solves Eqn. 1 and 2 by the use of the Finite Volume Method (FVM), coupled with the Volume of Fluid (VOF) technique to track the location of surfaces and to apply the proper dynamic boundary conditions at those surfaces. In addition, the Generalized Minimum Residual Solver (GMRES) is used to solve the pressure and the velocities.

Description of the CFD Model

The parameters of the infiltration process, such as material properties, the geometry of the mold, and the boundary condition used in this study are all adopted from [8], in order to make a comparison between the two different numerical approaches. A porous preform, having a shape of cylinder with a diameter of 10 cm and a height of 3 cm, is assumed to be inserted in a mold which covers all the surfaces of the preform except a 15-mm-diameter circular inlet on top of the preform, see the grey region and blue region in Fig. 1, respectively. A vacuum of 50 Pa is applied as the void initial state, and an external pressure of 0.8MPa is used as inlet boundary condition to force the molten aluminum to flow into the preform. Furthermore, a zero-velocity boundary condition is used at the surface of the porous preform. Finally, two symmetry boundary conditions are used between the red and grey/blue region of the domain, shown in Fig. 1, which enables only one fourth of the preform to be simulated and thereby reducing the calculation time. Note that in this preliminary study, the size of the control volumes is set equal to the mean diameter of spherical particles in order to decrease the computational load.

In addition, the molten aluminum is considered to be A380 with a dynamic viscosity of 0.0012 Pa·s and a density of 2.46×103 kg/m^3, while the material of the spherical particles is assumed to be glass. These are both common materials used to produce ASF by infiltration process.

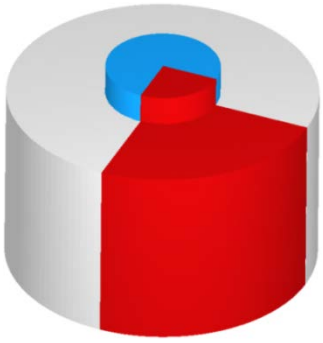

Figure 1: Schematic view of preform and inlet. The red subdomain represents the part of the geometry simulated by the numerical model.

Geometric Model of Porous Preform

The three-dimensional geometrical model of a preform consists of spherical particles is then generated based on the following assumptions: the shape of the spherical particle is considered to be a cube; these cubes are randomly distributed inside the preform; the total volume fraction of the cubes is 33%.

The preform is created as described below. The computational domain of the preform is divided into many small cubes. The side length of an individual small cube is considered to be the mean diameter of the spherical particles. Afterwards, each small cube has one in three chance of being a spherical particle. Therefore, a porous preform consists of small cubes (represent for spherical particles) is obtained, see Fig. 2, and the volume fraction of the fibers is approximately 33%.

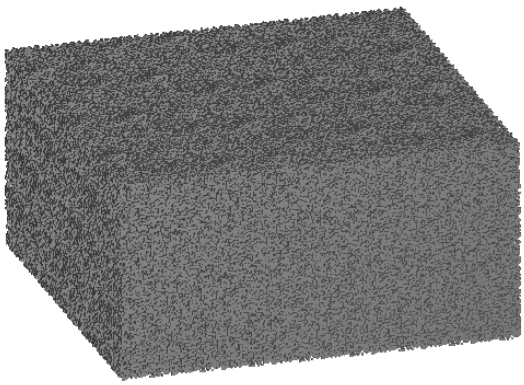

Figure 2: Schematic view of geometric model of the preform.

Afterwards, the STL file of the preform is imported into FLOW-3D and trimmed in order to have the same shape of a quarter of a cylinder, see Fig. 3.

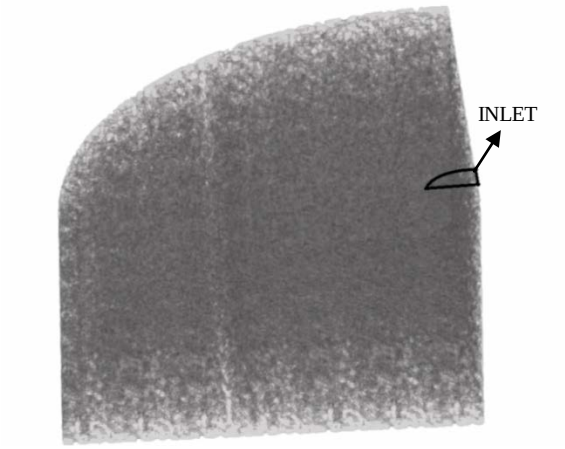

Figure 3: Computational domain in the CFD model.

RESULTS AND DISCUSSION

Flow Pattern

The simulated flow pattern of the molten aluminum of different cases is shown in Figs. 4. The mean diameter of spherical particles is 500 µm, 400 µm, 300 µm, and 200 µm, respectively. The red region represents for the molten aluminum and the grey region represents for the preform.

The simulated infiltration flow pattern is very similar to the one presented in [8] which utilizes a porous media/permeability approach. The infiltration front appears to be hemispherical. It shows the capacity of this CFD approach to capture the physics involved during the infiltration process.

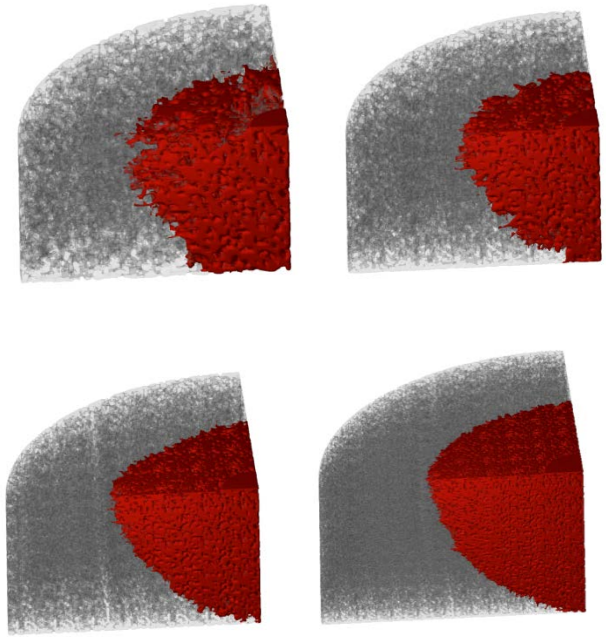

Figure 4: Flow propagation of molten aluminum in porous preform.

Moreover, the flow pattern at the symmetry boundary shown in Fig. 5 shows the value of fluid fraction. That means it is possible to capture the volume fraction of air, which is also the unintended porosities, during the infiltration process. The dangerous area with high risk of unintended porosities can be predicted using the CFD approach. Ideally, if the thermal equations are included in this model, the unintended porosities inside the preform can be predicted at the end of the infiltration process. However, in this preliminary study, thermal calculation has not been considered yet.

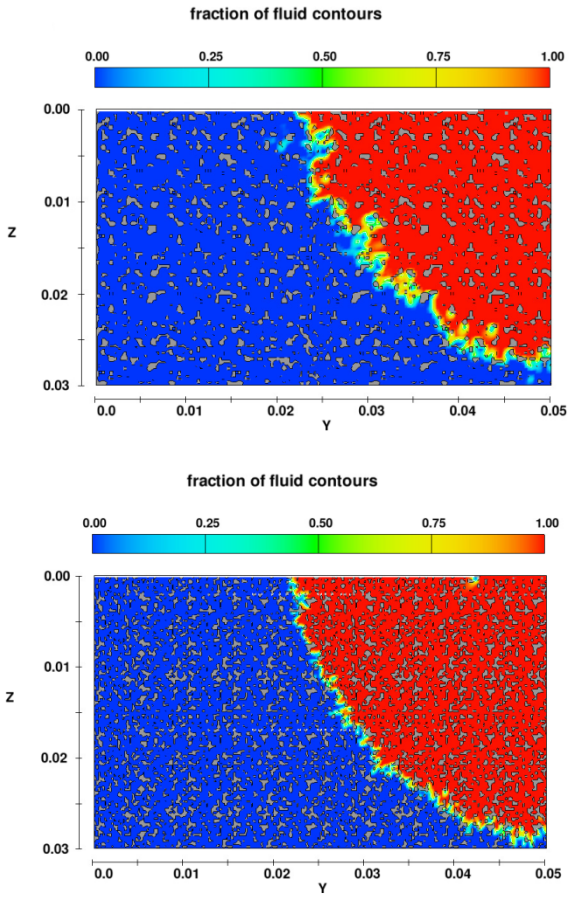

Figure 5: Flow propagation of molten aluminum in porous preform at symmetry boundary.

Filling time

The relationship between filling time and filling fraction is found to be linear according to the simulation results. And the filling time for simulations with 500 µm, 400 µm, 300 µm, and 200 µm-spherical-particle-diameter preform is 0.079s, 0.088s, 0.10s and 0.12s, respectively. The filling time is increasing when the size of the spherical particles is decreasing. Afterwards, the best fit curve of the relationship between filling time and filling fraction can be extrapolated, shown in Fig. 6.

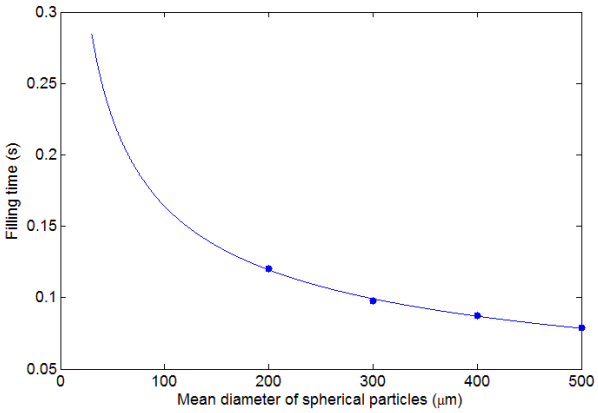

Figure 10: The relationship between the size of spherical particles and filling time.

Calculation time

If the size of the spherical particles decreases, the number of control volumes in the CFD model increases exponentially. In the meanwhile the computational load is getting much heavier. The calculation time for simulations with 500 µm, 400 µm, 300 µm, and 200 µm-spherical-particle-diameter preform is 6 hours, 13 hours, 30hours, and 200 hours, respectively. Therefore, it is feasible to carry out a simulation of infiltration process with a preform consists of spherical particles with the size of the order of 200 µm within a reasonable time using the CFD model.

CONCLUSIONS

A CFD approach presented in this paper shows a good potential to predict unintended porosities in Aluminum Syntactic Foam fabricated by infiltration process.

First, the simulated flow pattern using a CFD approach is very similar to the one using a porous media/permeability approach. It is possible to calculate the local unintended porosities during the infiltration process. Secondly, the filling time increases when decreasing the size of the spherical particles in the preform. Finally, the CFD approach can be used to simulate the infiltration process producing ASF with spherical particles which have a diameter of the order of 200µm.

Regarding the future work, a thermal calculation should be included in the CFD approach with a goal of obtaining the unintended porosities in the end of the infiltration process. Moreover, infiltration experiments should be conducted and compare the experimental results with numerical results.

ACKNOWLEDGMENTS

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REFERENCES

1. J. Banhart. "Manufacturing, Characterization and Application of Cellular Metals and Metal Foams", Progress in Materials Science, 46(6), 2001, pp. 559-632.
2. P.K. Rohatgi, D. Weiss, and N. Gupta. "Applications of Fly Ash in Synthesizing Low-Cost MMCs for Automotive and Other Applications", JOM, 58(11), 2006, pp. 71-76.
3. M.A. Navacerrada, P. Fernández, C. Díaz, and A. Pedrero. "Thermal and acoustic properties of aluminium foams manufactured by the infiltration process", Applied Acoustics, 74, 2013, pp. 496-501.
4. X.F. Tao, and Y.Y. Zhao. "Compressive behavior of Al matrix syntactic foams toughened with Al particles", Scripta Materialia, 61, 2009, pp. 461-464.
5. P. K. Rohatgi, J. K. Kim, N. Gupta, S. Alaraj, and A. Daoud. "Compressive characteristics of A356/fly ash cenosphere composites synthesized by pressure infiltration technique", Composites Part A: applied science and manufacturing, 37, 2006, pp. 430-437.
6. P.K. Rohatgi, R.Q. Guo, P. Huang, and S. Ray. "Friction and Abrasion Resistance of Cast Aluminum Alloy-Fly Ash Composites", Metallurgical and Materials Transactions A, 28(2), 1997, pp. 245-250.
7. J.G. Wu, and L.C. Wang. "Study on Preparation and Impact Performance of the Aluminium Foam Reinforced by ZrO2 Spheres" Materials Science Forum, 704-705, 2012, pp. 1029-1034.
8. T. Dopler, A. Modaressi, and V. Michaud. "Simulation of Metal-Matrix Composite Isothermal Infiltration Processing". Metallurgical and Materials Transactions B, 31B, 2000, pp. 225-234.
9. P. Damronglerd, and Y.W. Zhang. "Numerical simulation of solidification of liquid copper saturated in porous structures fabricated by sintered steel particles", International Journal of Numerical Methods for Heat & Fluid Flow. 22(1), 2012, pp. 94-111.
10. A.T. Krummel, S.S. Datta, S. Münster, and D.A. Weitz. "Visualizing Multiphase Flow and Trapped Fluid Configurations in a Model Three-Dimensional Porous Medium", AIChE Journal, 59(3), 2013, pp. 1022-1029.
11. FLOW-3D User's Manual, version 10.1.