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Three-dimensional finite element model for metal displacement and heat transfer in squeeze casting processes

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Abstract

A three-dimensional finite element model for the numerical simulation of metal displacement and heat transfer in the squeeze casting process has been developed. In the model, a numerical approach, termed as 'Quasi-static Eulerian', is proposed, in which the dynamic metal displacement process is divided into a certain number of sub-cycles. In each of the sub-cycles, the dieset configuration is assumed to be static and a fixed finite element mesh is created, thus making the Eulerian approach applicable to the solution of metal flow and heat transfer. Mesh-to-mesh data mapping is carried out for any two adjacent sub-cycles to ensure that the physical continuity of the real metal displacement process is represented. A numerical example is presented, which shows the application of the present model to geometrically complex three-dimensional squeeze casting problems. ***To cite this article: R.W. Lewis et al., C. R. Mecanique 335 (2007).***

Résumé

Modèle d'éléments-finis tridimensionnel pour le déplacement de métal et transferts de chaleur lors de moulage forgeage. Un modèle tridimensionnel basé sur l'approche éléments-finis à été développé pour la simulation numérique du déplacement du métal et des transferts thermiques lors du processus de moulage–forgeage. Dans le modèle, l'approche numérique, dénommée « Quasi-static Eulerian » est proposée, où le déplacement de métal est divisé en un certain nombre de sous-cycles. Dans chaque sous-cycle, la configuration est supposée être statique et un maillage élément-finis fixe est généré, ceci permettant l'utilisation de l'approche Eulérienne à la solution du métal en écoulement et aux transferts de chaleur. Le traitement d'information de grille à grille est possible entre les deux sous-cycles adjacents et permet d'assurer et de représenter la continuité physique du processus de déplacement réel du métal. Un exemple numérique est présenté, et montre l'application du présent modèle à des géométries complexes tridimensionnelles de problème de moulage forgeage. ***Pour citer cet article : R.W. Lewis et al., C. R. Mecanique 335 (2007).***

Keywords: Computational fluid mechanics; Squeeze casting; Finite-element; Punch

Mots-clés : Mécanique des fluides numérique ; Moulage forgeage ; Eléments-finis ; Poinçon

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Version française abrégée

Une analyse par voie numérique des instabilités et bifurcations dans un bain fondu de croissance cristalline a été réalisée en présence de surface libre ou rigide. La méthode de localisation du front à base d'une formulation de type enthalpie–porosité a permis d'étendre l'analyse à la présence du front de solidification. Les instabilités d'interface en interaction avec les régimes étudiés sont déterminées avec une précision comparable aux méthodes spectrales. Des surfaces conductrices libres ou rigides ont étés considérées. L'effet de quelques paramètres de contrôle liés au choix des matériaux (chaleur latente, écart de conductivités thermiques solide/liquide) sur le régime d'écoulement et les fluctuations du front de solidification a été analysé.

1. Introduction

Squeeze casting, which is also called squeeze forming or liquid metal forging in some cases [1,2], is the term commonly used to describe the process where liquid metal is solidified under the action of an external pressure. It is a near-net-shape process for converting liquid metal into a fully shaped component with precise dimensions, excellent surface quality and of a metallurgical integrity which is equivalent to that obtained in metal forging. The fundamentals of the process have been known for a long time, however, only in recent decades has the process been widely commercialized [3]. Nowadays, two different types of squeeze casting technologies have evolved, which have been given the names direct and indirect squeeze casting, based upon different approaches for metal metering and die filling [3,4]. In the indirect process, liquid metal is injected into the die cavity through a wide section gate by a small diameter piston, which also applies pressure during solidification. In the direct squeeze casting process, accurately metered liquid metal is first poured into the lower half of the die. Then, a platen held upper die (or punch) is actuated to move downwards and force the liquid metal to relocate within the die cavity. Immediately after the die halves close, the press force is applied onto the metal by means of the upper die. Not only does the sustained pressure eliminate shrinkage defects, it also ensures an intimate contact between the metal and the die. Thus, the solidification process is accelerated and the metallurgical structure improved.

This paper looks only at the direct squeeze casting process and concentrates mainly on the metal displacement and heat transfer during the die closure process. Many defects, such as air entrapment, slag inclusion and cold shuts may arise during this period and once these defects are formed in the solidified castings, then most of the techniques for improving mechanical properties such as microstructure refinement and heat treatment could become meaningless. Therefore, good die designs and appropriate process parameters are essential for producing high quality castings. Computer modelling is a powerful tool, by which the process parameters could be optimized for an existing process and the designs of die cavity structure for a new process could be based on effective guidance.

As a typical numerical approach, the finite element method has been used successfully in modelling the mould filling process of conventional castings [5–8]. However, not much work has been done on modelling the metal displacement in the squeeze casting process, except for the early work by Gethin et al. [9]. Here, an approximate method was employed to take the effect of metal displacement into account in the numerical simulation of squeeze casting processes.

The modelling of the metal displacement involves two important issues, i.e. tracking the free surface and dealing with the boundary between the liquid metal and the upper die. Both of these are moving boundary problems. Most approaches for dealing with such moving boundary problems can be classified into three groups, i.e. Lagrangian [10,11], Eulerian [5–7,12], and arbitrary Lagrangian–Eulerian (ALE) [13,14]. The Lagrangian approach, where the mesh moves with the considered object, is suitable for problems where the mesh does not experience large distortion. However, for flow problems, the motion of the mesh may lead to unacceptable element entanglement. The Eulerian approach, in which a fixed mesh is employed, has a good performance for free surface tracking where the volume of fluid (VOF) method or its variants are normally used. However, it is difficult to use only one fixed mesh to deal with the moving punch boundary in the squeeze casting process. ALE appears to be a valuable alternative, which allows the mesh to move arbitrarily in dealing with the moving punch boundary and also tracking the free surface without severe mesh distortion. However, for three-dimensional flow problems with complex geometry, the implementation of ALE is not straightforward because the mesh has to be frequently moved, mended, and even regenerated, which obviously could cause serious computational problems.

In this article, a three-dimensional finite element model for the numerical simulation of metal displacement and heat transfer in the squeeze casting process has been developed. In the model, a numerical approach, termed as 'Quasi-static Eulerian', is proposed, in which the dynamic metal displacement process is divided into a certain number of sub-cycles. In each of the sub-cycles, the dieset configuration is assumed to be static and a fixed finite element mesh is created, thus making the Eulerian approach applicable to the solution of metal flow and heat transfer. Mesh-to-mesh data mapping is carried out for any two adjacent sub-cycles to ensure that the physical continuity of the real metal displacement process is represented. The Navier–Stokes equations are used to describe the metal displacement process and are discretized by using a conventional Galerkin method. An implicit, or backward Euler method, is used in the temporal discretization of the flow governing equations. The free surface variation during the metal displacement process is tracked by solving a pseudo-concentration function, which is a hyperbolic or pure convection equation, by using the Taylor–Galerkin method. The Taylor–Galerkin method is also used to solve the heat transfer problem in the process. Finally, a numerical example is presented, which shows the application of the present model to geometrically complex three-dimensional squeeze casting problems.

2. Mathematical model and finite element formulation

2.1. Quasi-static Eulerian approach

The metal displacement in the die closure process is a dynamic process in which the flow of the liquid metal is driven by the continuously downward movement of the punch or upper die. At the same time, the metal front rises in the die cavity and in some cases where the die has secondary cavities overspill may take place as well. In this process, the whole die cavity, including the filled and unfilled space, decreases and all of the molten metal is forced to relocate in the varying die cavity. At the end of the closure process, the molten metal assumes the final shape of the cavity.

The above brief review of the metal displacement process leads to the following concept. The continuous punch movement can be divided into a series of discrete steps, each of which corresponds to a different punch position. In each step, a static dieset configuration and its finite element mesh can be employed to model the fluid flow and track the free surface (Eulerian approach). The combination of all the steps represents approximately the dynamic process. That is the reason why the present method is termed as 'Quasi-static Eulerian' approach. Here, each of the steps is referred to as a subcycle, and any two adjacent subcycles are linked by data extrapolation for the associated variables from the former mesh to the latter one.

A velocity boundary condition is imposed at the interface between the punch and the liquid metal to simulate the effect of the punch action, which is shown schematically in Fig. 1. Normally, the punch only moves in the vertical direction and normal velocities are applied to determine the local orientation of the punch surface. In addition, the punch–metal interface may vary with the movement of the metal front. Therefore, the location of the velocity boundary condition depends upon the position of the metal front itself.

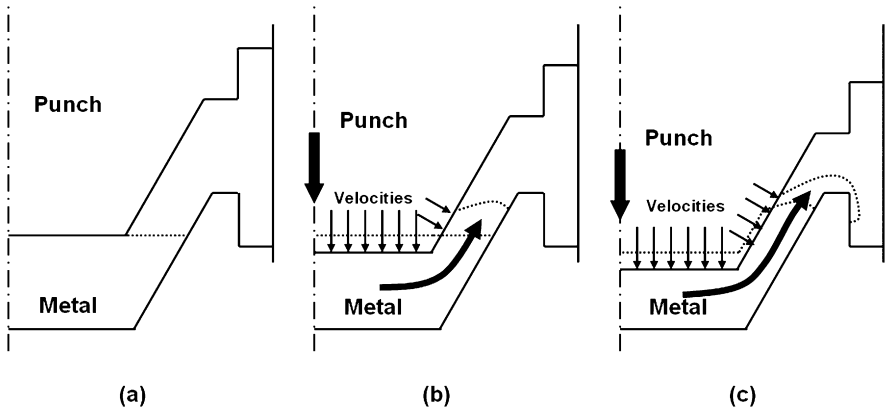

Fig. 1. Schematics of dealing with punch movement.

Fig. 1. Schéma du mouvement du poinçon.

The total volume of the molten metal is kept constant provided that any volume change caused by cooling and/or solidification is negligible. Therefore, global volume conservation must be ensured in the simulation.

2.2. Fluid flow

The flow of liquid metal may be assumed to be Newtonian and incompressible. The governing Navier–Stokes equations, which represent the conservation of mass and momentum, are given below in terms of the primitive flow variables, i.e. the velocity vector $\mathbf{u}$ and pressure p:

$$\nabla \cdot \mathbf{u} = 0 \tag{1}$$

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + (\mathbf{u}\cdot\nabla)\mathbf{u}\right) = \nabla\cdot\mu\left[\nabla\mathbf{u} + (\nabla\mathbf{u})^{\mathrm{T}}\right] - \nabla p + \rho\mathbf{g} \tag{2}$$

The flow in the entire domain (filled/empty) is treated as a single-phase flow with space-dependent properties. The values of density and viscosity of the empty region have to be chosen such that the flow of the metal is not affected by the particular values used. In the present work, the density of air is assigned to the empty region. The kinematic viscosity of the empty region is assumed to be the same as that of the liquid metal. For elements which contain the free surface, weighted average values are assigned for the properties. The boundary conditions can be formulated in the form of pressure and/or velocities at the boundaries:

$$\sigma_n = -p + 2\mu\frac{\partial u_n}{\partial n}, \qquad \sigma_\tau = \mu\left(\frac{\partial u_n}{\partial \tau} + \frac{\partial u_\tau}{\partial n}\right) \tag{3}$$

where the u_n and u_τ are the normal and the tangent velocities to the boundary.

Eqs. (1), (2) and (3) are discretized in space by using the conventional Galerkin finite element method. A 'mixed', or 'integrated', solution approach is adopted, in which the velocity and pressure values are computed simultaneously. The velocity field is approximated by quadratic shape functions and for the pressure term a linear interpolation is used to ensure a consistent and stable approximation. 10-node tetrahedral elements are used with velocity values assigned to all the 10 nodes, and pressure unknowns considered only for the corner nodes (mixed interpolation). In the variational formulation of the problem the derivatives do not appear; in consequence, the pressure field requires a lower order of approximation than the velocity field [15]. The space-discretized equation may be written in the following matrix form:

$$\begin{bmatrix} M_u & 0 & 0 & 0 \\ 0 & M_v & 0 & 0 \\ 0 & 0 & M_w & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{u} \\ \dot{v} \\ \dot{w} \\ \dot{p} \end{bmatrix} + \begin{bmatrix} K_{uu} & K_{uv} & K_{uw} & C_u \\ K_{vu} & K_{vv} & K_{vw} & C_v \\ K_{wu} & K_{wv} & K_{ww} & C_w \\ C_u^{\mathrm{T}} & C_v^{\mathrm{T}} & C_w^{\mathrm{T}} & 0 \end{bmatrix} \begin{bmatrix} u \\ v \\ w \\ p \end{bmatrix} = \begin{bmatrix} F_u \\ F_v \\ F_w \\ 0 \end{bmatrix} \tag{4}$$

where M is the mass matrix, K is the velocity stiffness matrix which contains the advection and viscous terms, C^{T} is the divergence matrix and F denotes the force vector. A fully implicit (backward Euler) method is used for the temporal discretization, finally yielding a system of nonlinear equations.

Normal velocities are prescribed, as mentioned above, at the punch–metal boundary while slip boundary conditions are applied to the boundary between the metal and the fixed dieset. The slip boundary conditions are found to be sufficient in the metal casting applications. The results obtained from the plane version of the program were compared with the Birmingham benchmarks giving good flow patterns [16].

The nonlinear equation system is solved by using an iterative procedure. In nonlinear iterations, the multifrontal massively parallel solver (MUMPS) [17] is employed to solve the linear system of equations for the velocity and pressure unknowns.

2.3. Free surface tracking

The free surface movement is governed by the following first order pure advection equation:

$$\frac{\partial F}{\partial t} + (\mathbf{u}\cdot\nabla)F = 0 \tag{5}$$

where F is the pseudo-concentration function, which is defined as a continuous function varying between -1 and 1 across the elements lying on the free surface. The value of $F = 0$ is used to locate the free surface at a given time, with $F > 0$ indicating the fluid region and $F < 0$ indicating the empty region.

The pseudo-concentration function is approximated by linear shape functions using 4-node tetrahedral elements. For this purpose, the 10-node tetrahedral elements used in the flow computation are divided into 4-node sub-elements. Eq. (5) is discretized by using the Taylor–Galerkin scheme [18] to avoid the oscillations which occur when the conventional Galerkin method is adopted. This results in a system of equations of the form:

$$M_F\left(\frac{F_{n+1} - F_n}{\Delta t_{\text{exp}}}\right) + K_F F_n = 0 \tag{6}$$

where K is the Taylor–Galerkin advection matrix and Δt_{exp} is the time step for free surface tracking. An iterative explicit procedure, which requires both the lumped and consistent forms of the mass matrix M, is employed. Details of the advective matrix and the iterative explicit procedure can be found in [19]. The pseudo-concentration function is redefined at regular intervals in order to maintain its sharpness [20].

2.4. Heat transfer

The energy equation for calculating the temperature distribution in liquid metal is given below:

$$\rho c\left(\frac{\partial T}{\partial t} + \mathbf{u}\cdot\nabla T\right) = \nabla\cdot k\nabla T \tag{7}$$

The convection term on the left-hand side of this equation couples the flow field and the temperature. The die region has no convection term, and the metal–die interfacial heat transfer is taken into account by using interface elements based on the following equation:

$$\left(-k^m\frac{\partial T^m}{\partial n}\right)_i = \left(k^d\frac{\partial T^d}{\partial n}\right)_i = h_i\left(T^m - T^d\right)_i \tag{8}$$

where n is the outward normal to the metal surface, h_i is the heat transfer coefficient, and m, d, and i denote metal, die, and interface respectively. In some cases, the heat loss due to the interface heat transfer may be high enough to cause solidification during the metal displacement process. The latent heat release in solidification is taken into account approximately by using an effective specific heat which is calculated with the equation:

$$c_{\text{eff}} = \sqrt{\frac{\nabla h\cdot\nabla h}{\nabla T\cdot\nabla T}} \tag{9}$$

where h is the specific enthalpy and defined as:

$$h = c_p T + (1 - f_s)L \tag{10}$$

where L is the latent heat, and f_s is the solid fraction and calculated by:

$$f_s = \begin{cases} 0, & T \geqslant T_l \\ (T_l - T)/(T_l - T_s), & T_s < T < T_l \\ 1, & T \leqslant T_s \end{cases} \tag{11}$$

where T_l and T_s are the liquidus and solidus temperatures, respectively.

The energy equation (7) is also discretized by using the Taylor–Galerkin method based on the 4-node tetrahedral elements derived from the 10-node tetrahedral elements. The final discrete equation is in the following form:

$$\left(\frac{M}{\Delta t_{\text{exp}}} + \frac{K_d}{2}\right)T_{n+1} = \left(\frac{M}{\Delta t_{\text{exp}}} - \frac{K_d}{2} - (K_a + K_{bd})\right)T_n \tag{12}$$

where M is the thermal capacitance matrix, K_a, K_d, and K_{bd} are the temperature stiffness matrices for convection, diffusion, and balancing diffusion, respectively.

2.5. Computational strategy

An implicit–explicit coupling approach is employed in the model solution. The metal flow is computed by a fully implicit scheme with larger time steps (Δt) for the sake of stability and computational speed. The metal front is tracked by using an iterative explicit Taylor–Galerkin scheme with smaller time steps (Δt_{exp}) so that the front does not 'jump' more than one cell within any time step. The temperature is calculated after each front-tracking step with the same step size. The value of the implicit time step is chosen such that it encompasses 30–60 explicit front-tracking steps. Typical values for the implicit step range from 0.005 to 0.025 s. This implicit-flow and explicit- front and temperature combination makes the computation more efficient, having both the stability of the implicit method and the speed of the explicit method.

3. Numerical simulation example

In the present study, an aluminium alloy squeeze cast is simulated to demonstrate the capability of the developed model. The geometry of the final casting and the initial metal-dieset configuration are shown in Fig. 2. The initial metal-dieset assembly is displayed as a section for a clear view of the internal structure. The length of the casting is 270 mm, the width 100 mm, the height 80 mm, and the wall thickness 10 mm. The total displacement of the punch from its immediate contact on the metal surface to the end of the die closure process is 11 mm and this is divided into 11 equal displacement increments in the simulation, which is believed to adequately capture the necessary details. The moving speed of the punch is 10.0 mm/s and the whole metal displacement process lasts 1.1 s. The initial temperature of the liquid metal is 690 °C , and that of the dieset is 270 °C. The thermophysical data used in the simulation are listed in Table 1.

Fig. 3 shows the calculated velocity vector distribution in the die closure process. It can be seen that with the punch movement, the velocities of the metal flow are increased significantly due to the fact that the die cavity decreases whereas the punch still keeps moving at a constant pace. This result coincides with one's intuition. Fig. 4 shows the three-dimensional shape of the metal front corresponding to the movement shown in Fig. 3. The metal displacement process depends mainly on the geometry of the die cavity and the speed of the punch. An optimized die cavity design and a suitable punch speed are very important for achieving improved flow patterns. A low punch speed during the latter stages could be beneficial to obtaining a smooth flow at the end of the die closure process. Fig. 5 shows an example of the calculated temperature distribution in the metal, where only a slice is displayed for a clear view. In summary, the above simulation results show that the present model has the ability to provide detailed information about what happened in the invisible die cavity, which can be used to guide the process design and optimization of the squeeze casting process.

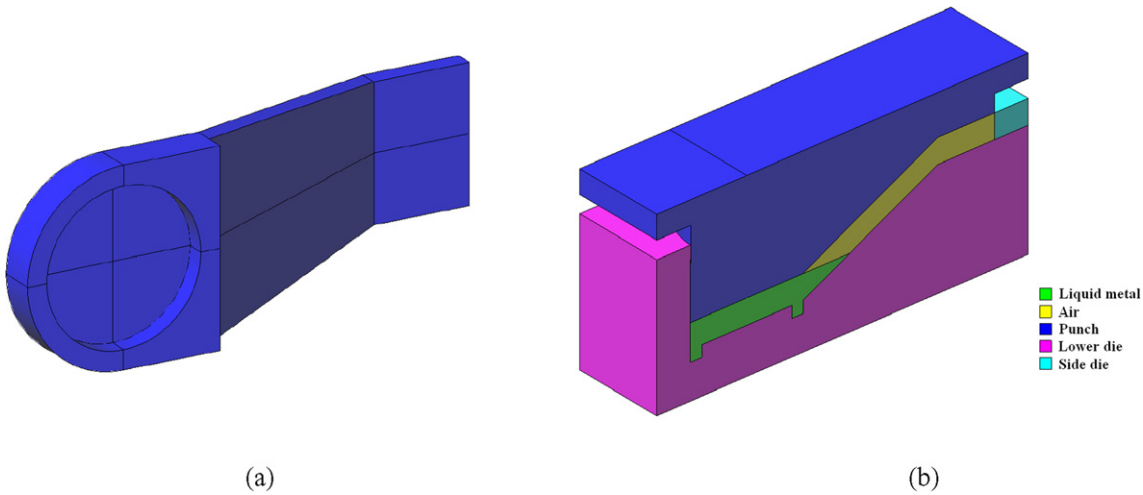

Fig. 2. (a) Final casting geometry and (b) initial metal–dieset configuration.

Fig. 2. (a) Géométrie finale moulée et (b) configuration initiale du métal–dieset.

Table 1
Thermophysical data for numerical simulation

Tableau 1
Données thermophysique pour la simulation numérique

Parameter	Value
Metal density, kg/m^3	2680.0
Metal specific heat, J/(kg °C)	1093.0
Metal thermal conductivity, W/(m °C)	186.3
Latent heat, J/kg	3.26×10^5
Liquidus temperature, °C	615.0
Solidus temperature, °C	550.0
Die density, kg/m^3	7721.0
Die specific heat, J/(kg °C)	712.0
Die thermal conductivity, W/(m °C)	33.9
Heat transfer coefficient, W/(m^2 °C)	2000.0

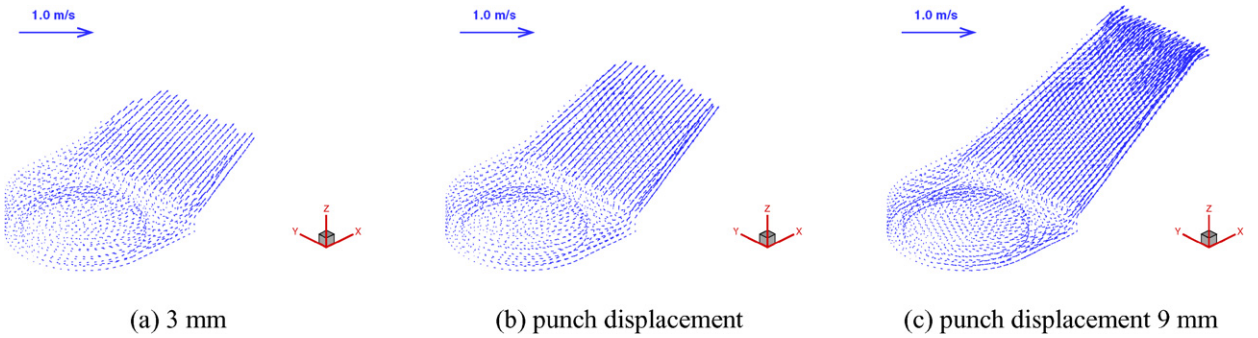

Fig. 3. Calculated velocity vector in the die closure process for different punch displacement: (a) 3 mm, (b) 6 mm, and (c) 9 mm.

Fig. 3. Vecteur de vitesse calculé lors du processus de fermeture de matrice pour différents déplacements du poinçon : (a) 3 mm, (b) 6 mm et (c) 9 mm.

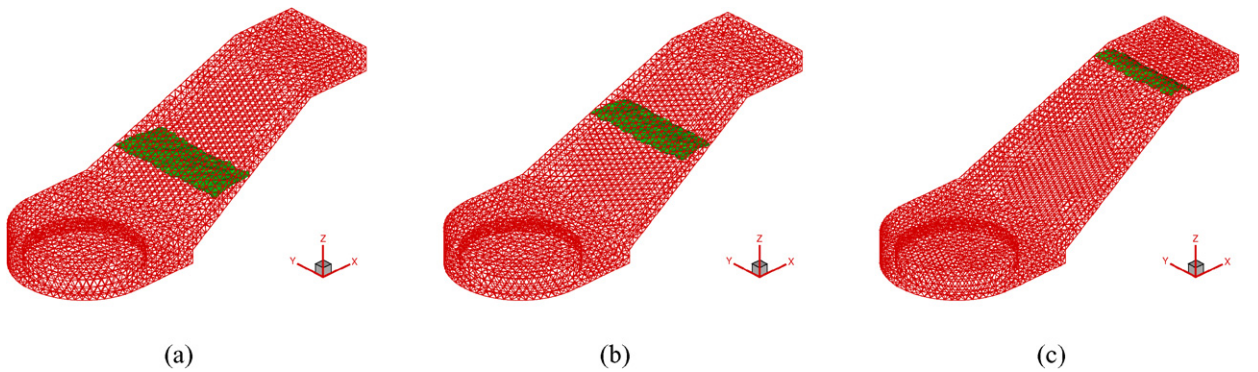

Fig. 4. Three-dimensional shape of the metal front, for different punch displacement: (a) 3 mm, (b) 6 mm and (c) 9 mm.

Fig. 4. Forme tridimensionnelle du front de métal pour différentes déplacements du poinçon : (a) 3 mm, (b) 6 mm and (c) 9 mm.

4. Conclusion

A three-dimensional finite element model for the numerical simulation of metal displacement and heat transfer in the squeeze casting process has been presented, in which a numerical approach termed as 'Quasi-static Eulerian' was proposed for dealing with the moving punch boundary and tracking of the free surface. A numerical example of an aluminium alloy casting has been presented, which shows the capability of the developed model to simulate the metal

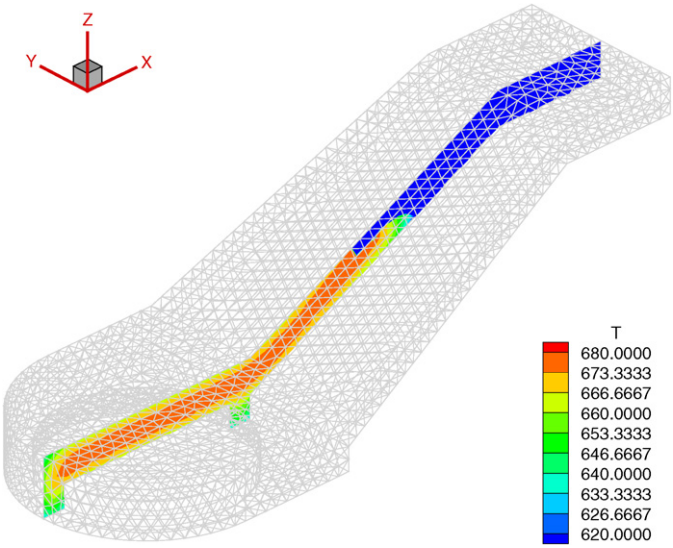

Fig. 5. Temperature distribution on the middle section (punch displacement 6 mm).

Fig. 5. Distribution de température dans le plan médian (déplacement du poinçon 6 mm).

displacement and heat transfer in the squeeze casting process. The coupling of metal flow and heat transfer ensures that the model is capable of providing realistic and useful information, which can be used not only to analyze any casting defects associated with the die closure process but also to carry out further simulations on the pressurized solidification process.

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