Effects of centrifugal and Coriolis forces on the mold-filling behavior of titanium melts in vertically rotating molds

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Abstract: The vertical centrifugal-casting technique is widely used in the manufacture of various irregularly-shaped castings of advanced structural alloys with thin walls, complex shapes and/or large sizes. These castings are used in the increasing applications in aero-space/aviation industries, human teeth/bone repairs with near-net shaped components, etc. In a vertically rotating casting system, the mold-filling processes of alloy melts, coupled with solidification-heat transfer, may be much more complicated, because they are driven simultaneously by gravity, centrifugal and Coriolis forces. In the present work, an N-S/VOF-equations-based model, solved using a SOLA-VOF algorithm, under a rotating coordinate system was applied to numerically investigate the impacts of centrifugal and Coriolis forces on metallic melt mold-filling processes in different vertical centrifugal-casting configurations with different mold-rotation rates using an authors' computer-codes system. The computational results show that the Coriolis force may cause remarkable variations in the flow patterns in the casting-part-cavities of a large horizontal-section area and directly connected to the sprue via a short ingate in a vertical centrifugal-casting process. A "turn-back" mold-filling technique, which only takes advantage of the centrifugal force in a transient rotating melt system, has been confirmed to be a rational centrifugal-casting process in order to achieve smooth and layer-by-layer casting-cavities-filling control. The simulated mold-filling processes of Ti-6Al-4V alloy melt, in a vertical centrifugal-casting system with horizontally-connected plate-casting cavities, show reasonable agreement with experimental results from the literature.

Key words: centrifugal casting; Coriolis force; mold-filling; solidification-heat transfer; computer simulation

CLC number: TG146.2$^+$3 Document code: A Article ID: 1672-6421(2008)04-0249-09

The conventional centrifugal-casting technique was mostly used to produce cylinder-like castings of various diameters and various alloys since the 40s of the last century [1,2]. To make these symmetrical castings, both horizontally and vertically rotating molds can be adopted, depending on the length-to-diameter ratios of the castings. However, with increasing special applications of advanced structural alloys, e.g. titanium-based alloys in aero-space / aviation industries etc., the vertical centrifugal-casting technique is now widely used in the manufacture of various irregularly-shaped castings with thin walls and/or large sizes with high quality [2-9].

Compared with a gravity casting process, more complicated centrifugal-mold-filling behavior of alloy melts, caused by the complex driving forces, will be presented in a vertical centrifugal-casting process. Due to the mold rotation and the opacity of both the metallic melts and the mold materials, such complicated mold-filling and the coupled heat-transfer/solidification behavior is difficult to determine experimentally. Therefore, much research effort has been devoted to developing a numerical simulation technique and computer codes as a tool [8-16] for achieving a rational technological control for a centrifugal-casting process.

It is well known that in a rotating system, a mass moving/flowing radially away from the axis of rotation will receive an additional force, termed a Coriolis force [17]. This force may cause different mold-filling behavior in a vertical centrifugal-casting process, as revealed by hydraulic simulations [18]. In a previous numerical modeling by the present authors for the mold-filling behavior of Ti-6Al-4V melt in a vertical centrifugal-casting process [10-12], the emphases were placed on the impact of the centrifugal forces while the Coriolis effects were neglected. Despite such neglect, however, a full model simulation for a similar centrifugal casting system, carried out in reference [13], shows that the calculated results were basically similar to those of the authors, which indicates

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Received: 2008-06-28; Accepted: 2008-09-06

that the Coriolis force may exert a less important influence in some cases. Therefore, this article aims at investigating the influences of both the centrifugal and Coriolis forces on the mold-filling and the coupled heat-transfer behavior in an application-oriented vertical centrifugal-casting system, using general 3D-simulation purpose codes developed by the authors. Extensive computations are involved in the present numerical investigations on different vertical centrifugal-casting configurations with different mold-rotating rates.

1 Computational model

The configuration of the vertical centrifugal-casting system and the coordinate systems used are illustrated in Fig. 1 for the present modeling description. In the schematics, the dot-dot-dash lines define a mold-cavity into which the alloy melt is poured with an inlet velocity, V_o, and an initial temperature, T_P. The melt is allowed to flow freely and occupy the confined space. The mold, of different material(s) and at an initial temperature much lower than T_P, is not shown in the schematics for simplicity. In this simple centrifugal-casting system, two horizontal square plate-castings are symmetrically attached to the root of the vertical sprue via a short runner.

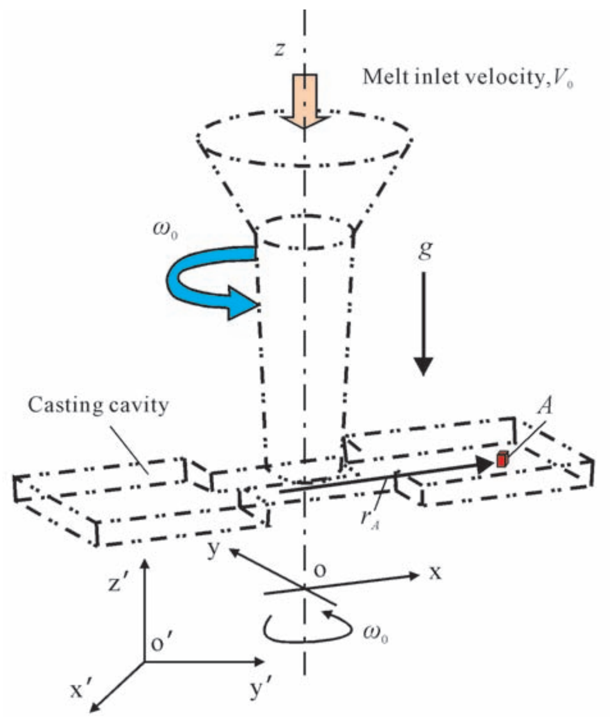

Fig. 1 Schematic vertical centrifugal-casting configuration and the coordinate systems

In the mold-filling and solidification processes, the casting mold system is made to rotate horizontally around the vertical axis of the sprue at a constant angular rate, ω_o, relative to the (static) laboratory coordinate system, x'-y'-z'. A rotating linear coordinate system, x-y-z, is chosen fixed to the turning mold system with the central axis of the sprue as the z-axis, see Fig. 1. For the application-oriented centrifugal-casting system shown in Fig. 2(b), a similar rotating coordinate system, x-y-z, is taken but using the jar-like sprue's axis as the turning z-axis.

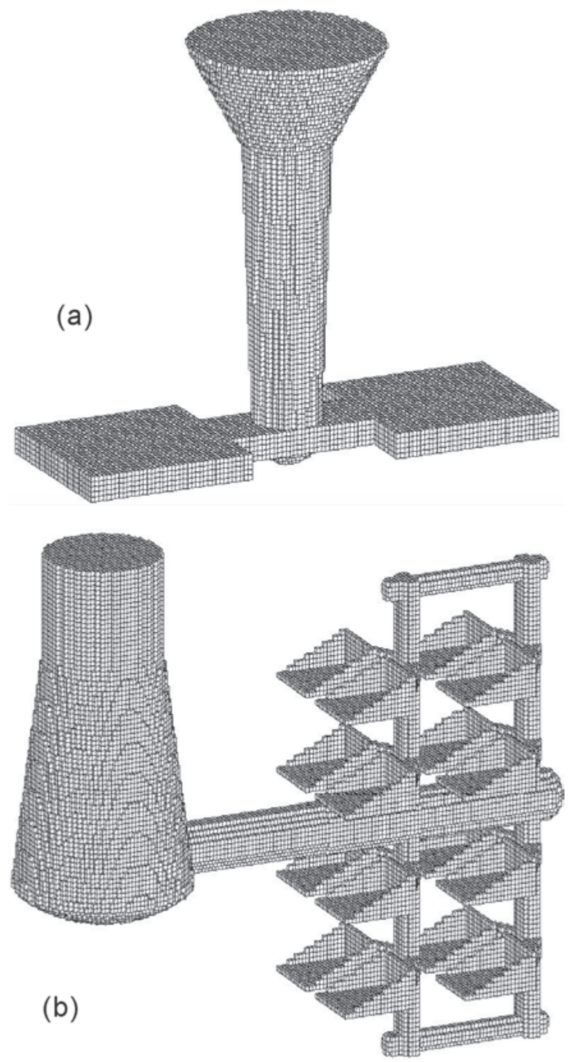

Fig. 2 Mesh patterns made in the present centrifugal-mold-filling simulations: (a) for experimental verification; (b) for an application-oriented modeling.

The governing equations for the centrifugal mold-filling and the coupled heat-transfer processes of an alloy melt are derived based on a control volume (CV) A, which is taken from the filling melt domain under the constantly rotating coordinate system, x-y-z, as shown in Fig. 1. Therefore, with the assumption of constant alloy properties, the mathematic model for the present numerical investigations may take the following formulation form:

Volume of fluid (VOF) equation

$$\frac{\partial F}{\partial t}+\nabla(\boldsymbol{v}F)=0 \tag{1}$$

Momentum transfer equation

$$\frac{\partial \boldsymbol{v}}{\partial t}+\nabla(\boldsymbol{v}\cdot\boldsymbol{v})=\gamma\nabla^2\boldsymbol{v}-\frac{1}{\rho_L}\nabla P+\boldsymbol{g}+\omega_n^2\boldsymbol{r}_A-2\boldsymbol{\omega}_o\times\boldsymbol{v} \tag{2}$$

Continuity equation

$$\nabla\cdot\boldsymbol{v}=0 \tag{3}$$

Heat energy transfer equation

$$\frac{\partial T}{\partial t}+\nabla\left(\boldsymbol{v}T\right)=\alpha\nabla^2 T+\frac{h}{c_p}\frac{\partial f_S}{\partial t} \tag{4}$$

In the present model, the vector symbol, $v = v_x i + v_y j + v_z k$, represents a melt-flow velocity relative to the rotating coordinate, x-y-z, system. The variable F in volume of fluid (VOF) Eq. (1) represents the volume fraction of flowing melt that occupies the CV concerned. VOF technique is typically employed to define and track the free surface of the mold-filling melt for a casting process [19], and is also adopted in the present numerical modeling for the centrifugal casting processes; t is the symbol for time. This modeling equation in fact forms an important part of the Mixed Interface-Tracking/Interface-Capturing Technique (MITICT), which has been more recently proposed and successfully applied to the finite element computations of flow problems by Akin, Tezduyar et al. [10-12]. In Eq. (4), T and f_S represent temperature and the volume solidified phase fraction, respectively; α represents thermal diffusion coefficient, $\alpha = \lambda / c_P \rho_L$, in which λ and ρ_L represent heat conductivity and density of fluid, respectively; h and c_P represent the latent heat and specific heat, respectively.

In the momentum transfer equation, Eq. (2), a Navier-Stokes equation with more external body-forces, the fourth term on the right-hand-side, $a_n = \omega_n^2 r_A$, represents the centrifugal acceleration, where r_A is the vector distance from the axis of rotation pointing to the mass-center of the concerned control melt-volume A, as shown in Fig. 1. g is the gravity vector and P represents pressure; γ is the kinetic viscosity of fluid. The absolute angular velocity of the A-CV, ω_n, i.e. in the lab-coordinate x'-y'-z', can be expressed as: [10-12]

$$\omega_n = \omega_o + (v_y \cos\theta - v_x \sin\theta)/|\boldsymbol{r}_A| \tag{5}$$

Where, θ is the angle between the x-axis and the projection of the vector r_A on the x-o-y plane. The last term on the right-hand-side of Eq. (2) represents the Coriolis acceleration [17], which can be viewed as a kind of inertia force.

SOLA-VOF algorithm [20, 21] is widely used in various casting-CAE computer codes for casting mold-filling computations. In the present work, this numerical solution technique is also employed to calculate the centrifugal mold-filling procedures (VOF-distribution), the relative velocity field, etc., but in a rotating coordinate system, based on the heat-transfer-coupled mathematical model of Eqs. (1) – (5) and a centrifugal casting configuration as illustrated by Fig. 1.

All the numerical computations are performed with authors-developed software, 3DLX-WSIM, for a general 3D-simulation purpose for various casting processes both only under gravity (setting $\omega_o = 0$) and in a rotating casting-mold system. The codes system consists of three main modules of pre-processing, numerical computation, and post-processing. The pre-/post-processing modules provide basic functions of 3D geometrical construction and meshing for a casting system, and 3D color-image presentations for the calculated results of different centrifugal mold-filling and coupled heat-transfer processes. All the computations by the simulation module and the color-image presentations by the pre-/post-processing modules can be performed on a PC-computer.

Two vertical centrifugal-casting configurations are designed for the present numerical investigations. The corresponding CV-meshed casting systems are shown in Fig. 2, which is an image output of the present computer codes. The first casting configuration, shown by Fig. 2(a), is primarily for the numerical model validation with centrifugal-casting experiments of Ti-6Al-4V melt quoted from the literature [22]. In the experiments of Suzuki et al.[22] two square plates of dimensions: 80 mm × 80 mm × 10 mm were cast using the vertical centrifugal-casting technique as depicted in Fig. 1. The entire cavity of the casting system, with maximum turning radius of ~ 120 mm, is meshed into 66924 cubic CVs of size 2 mm, Fig. 2(a). The second vertical centrifugal-casting system, shown in Fig. 2(b), is for an application-oriented configuration for multiple thin-wall Ti-6Al-4V castings, which is constructed with 144188 cubic CVs and with maximum turning radius of ~ 650 mm. This meshing model will be used for the numerical investigations of the centrifugal/Coriolis effects on a complicated casting system.

The properties data used for the model casting alloy of Ti-6Al-4V for the present computations are listed in Table 1. For the computation group of plate-castings of Fig. 2(a), for both numerical investigation and experimental verification, a temperature-dependent viscosity, expressed by Eq. (6), is employed instead of the constant viscosity.

For the present computations, the critical temperature, T_{Critic}, is taken as $T_{Critic} = T_{Liq} - 0.55(T_{Liq} - T_{Sol})$, below which the solidifying solid dendrites will form a rigid packed matrix blocking the bulk-flow of the alloy melt, where T_{Liq} and T_{Sol} represent the liquidus and solidus temperatures of the investigated alloy, respectively.

Table 1 The properties data used in the present computer simulations for Ti-6Al-4V alloy

Kinetic viscosity γ mm^2/s	Density ρ_L g/mm^3	Specific heat c_P J/g·°C	Heat conductivity λ W/mm·°C	Latent heat h J/g	Liquidus temperature, T_{Liq} °C	Solidus temperature T_{Sol} °C
0.954	4.44×10^{-3}	0.628	0.0155	375.72	1,635	1,522

Temperature-dependent vicosity:

$$\gamma(T) = \begin{cases} 4.1\text{E}-2\exp[6151/(273.15+T)], & T \geqslant T_{Liq} \\ 6.594\text{E}-9\ 4.1\text{E}-2\exp[6151/(273.15+T)], & T_{Liq} > T > T_{Critic} \\ 1000.0, & T \geqslant T_{Critic} \end{cases} \tag{6}$$

2 Experimental validation of model

According to the mathematic definition for the Coriolis force vector, $-2\omega_o \times v$, the Coriolis force directions in a vertical centrifugal casting system will be confined in a rotating plane, i.e. horizontally, and are normal to the flow directions of the melt CV concerned. Therefore, the centrifugal casting configuration for horizontal plate-castings, shown by Fig. 2(a), is suitable for investigating the impact of both the Coriolis and centrifugal forces on the casting-cavity filling behavior of alloy melts. The pouring velocity and the initial temperature of the Ti-6Al-4V melt are set to be V_o = –280 mm/s and T_P = 1,700 ℃, respectively, for the numerical simulations performed in this section.

A comparison between the calculated centrifugal-mold-filling behaviors in plate-casting cavities at a mold-rotation rate of 60 rpm with and without Coriolis-force considerations is shown by Fig. 3 in a VOF-display mode. The computational results of Figs. 3(a) to 3(c) are obtained using the full model of Eqs. (1) – (5), while the result of Fig. 3(d) is the output using a reduced mathematical model in which the Coriolis force term in the momentum transfer Eq. (2) was disabled. Figs. 3(a) and 3(b) give an outside view and a horizontal section view, respectively, for an early casting-cavity-filling behavior with clockwise (negative) mold-rotating direction. It can be seen that in this case, the horizontally spreading alloy melt, from the vertical pouring, flows towards the aproaching sides of the clockwise-turning plates-mold cavities, and then turns its flowing directions when touching the sidewalls of the mold-cavities, Fig. 3(b).

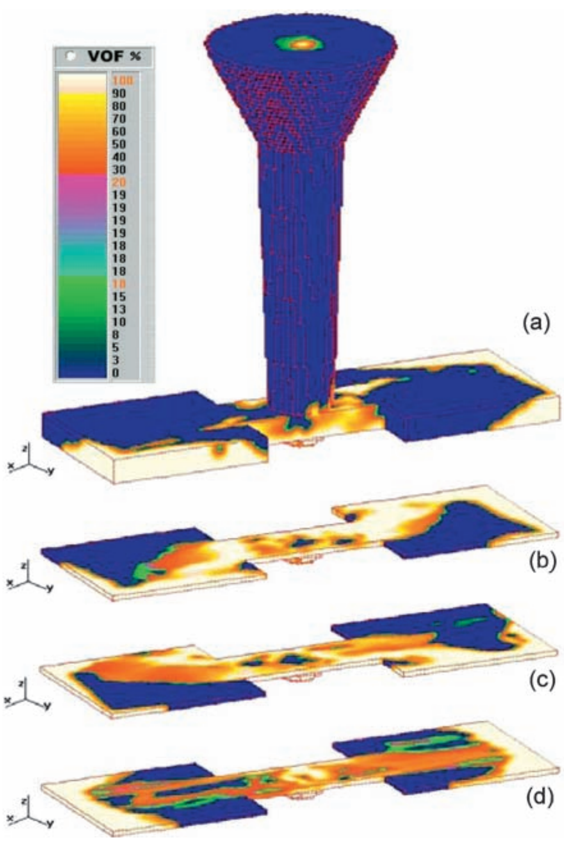

Fig. 3 Comparison between the calculated centrifugal-mold-filling behaviors in the plate-casting cavities, shown by Fig. 2(a), at a rotation-rate of -60 or 60 rpm with and without Coriolis-force considerations (an outside or horizontal section view for an early casting-cavity-filling stage): (a), (b) and (c) using the full simulation model of Eqs. (1)–(5) with clockwise/ negative (a)/(b) and counter-clockwise/positive (c) rotating directions, respectively; (d) without the Coriolis-force effect.

For the case of counter-clockwise (positive) mold-turning, the melt flow pattern in the casting cavities is closely similar to that of clockwise-rotating case, but towards the opposite sidewalls of the casting cavities as expected, because the Coriolis force is also rotation-direction dependent. Such a result is shown in Fig. 3(c). In both cases of Fig. 3(a)/3(b) and Fig. 3(c), the casting-cavities filling melts are also simultaneously driven by the centrifugal forces, whose directions are always away from the rotating axis. This phenomenon can be easily seen from Fig. 3(d), in which the Coriolis force was removed.

The simulation results comparison of Fig. 3 also shows that, the casting-cavity-filling pattern of the alloy melt in a vertical centrifugal-casting system may vary dramatically under a Coriolis-effect, if the casting-cavities of a large horizontal-section area are directly connected to the vertical sprue via a short ingate. Furthermore, the present full-model simulation results indicate that the direct mold-filling processes shown in Figs. 3(a) to 3(c) are not good for obtaining a sound casting, because with the further mold-filling proceeding, some gas holes, evolved from the melt-mold interface reactions, may be easily engulfed by the filling alloy melt. This casting-defect has been revealed by a similar titanium centrifugal-casting experiment carried out by Suzuki et al [22].

In the experimental work of Suzuki et al. [22], the authors employed a partial mold-filling technique to investigate the behavior of casting-cavity filling and gas hole entrapment with different mold-rotation rates from 100 to 400 rpm. Figure 4 gives a comparison between the present computational results (a) & (c) and Suzuki's experimental observations on 20 % partially-filled Ti-6Al-4V plate-castings at a mold-rotation rate of 200 rpm. Because the optical appearance of the partially-filled casting-parts, shown by Fig. 4(b) (i.e. Fig. 2(b) in reference [22]), was taken after the centrifugal-mold-filling experiment completed, only the shell part, resulted from the touch of the filling melt with the cold mold-walls, is available for comparison of the flow pass at that filling stage. The X-ray photographs, shown by Fig. 4(d) (Fig. 3 of reference [22]), taken for the left side of that shown in Fig. 4(b) represents the final solidified part under a steady rotating condition of 200 rpm, and can be used for comparison with steady melt VOF-pattern that partially filled in the constantly rotating casting mold. From Fig. 4, a reasonable agreement between the computational results and the quoted experiments can be seen.

3 Influences of mold-rotating velocities

The vertical centrifugal-casting system to be simulated in this section, as shown in Fig. 2(b), has a relatively complex

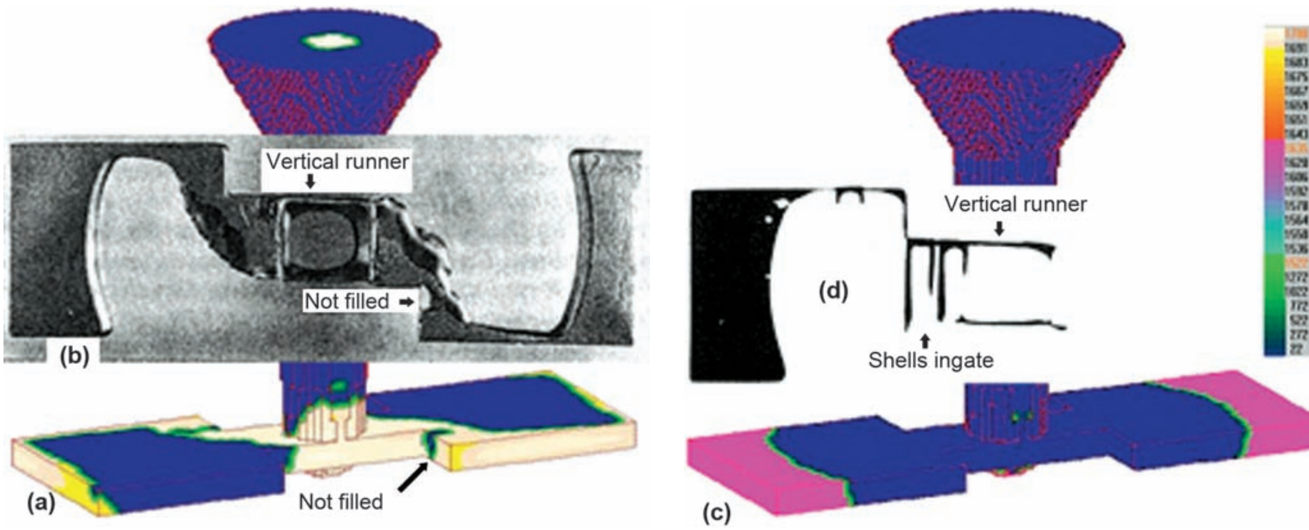

Fig. 4 Comparisons between simulation results (a) & (c) and quoted experimental observations (b) & (d)[22] for centrifugally cast horizontal plates of Ti-6Al-4V (20 % partially-filled) with a mold rotation-rate of 200 rpm: (a) and (c) show the simulation results for a plate-filling stage and final solidification stage, respectively; (b) and (d) give optical and X-ray photographs, respectively.

gating system, consisting of a rotating inlet-melt container (a special sprue), a horizontal runner and a vertical gating frame. 16 dustpan-like castings are attached to the vertical gating frame via a short in-gate in four columns and four layers. In this application-oriented configuration [23], a "turn-back" mold-filling technique is employed, which has been shown to be rational to ensure the casting's quality with a vertical centrifugal casting process [4, 16, 24]. The pouring temperature and the downward inlet-velocity of the alloy melt are assumed to be 1,700 ℃ and $V_o = -1{,}000$ mm/s, respectively, for the numerical investigations in this section.

During a centrifugal casting process, the casting mold is assumed to turn around the z-axis, which superposes with that of the downwards inlet-melt with a round section, at a constant angular velocity, ω_o. Effects of both the different magnitudes and directions of the mold-rotating velocity ω_o on the centrifugal mold-filling behavior will be tested in this computation section. All the 3D image-presentations in this section are output from the 3DLX-WSIM system in a VOF/temperature-composite-display mode. The different colors in the filling melt domains represent the corresponding temperatures of the alloy melts, as defined by the color-temperature (C-T) scale shown in each figure of the computational results.

To investigate the influences of the centrifugal force and Coriolis force on the mold-filling behavior separately, the Coriolis force term in Eq. (2) is again temporally removed for the following first computational series of Figs. 5 and 6.

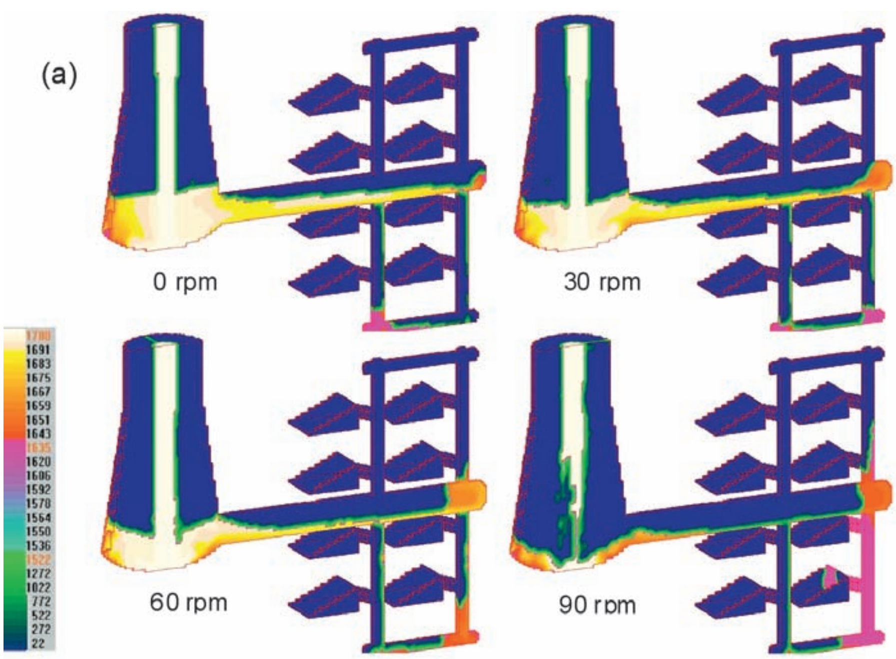

Figure 5 shows two comparison groups for the simulated centrifugal-mold-filling behavior at different mold-rotating velocities using the reduced model without Coriolis-effect consideration for an initial and an early casting-cavity-filling stage, respectively. From these calculated results, in a centrally-longitudinal-section view, it can be seen that under a mold-rotating condition the filled alloy melt, which possesses a stronger mold-filling ability compared to the gravity-casting case (i.e. zero mold-turning velocity, $\omega_o = 0$ rpm), tends to accumulate at the farthest end of the mold cavity. At the mold-turning velocity of ω_o =

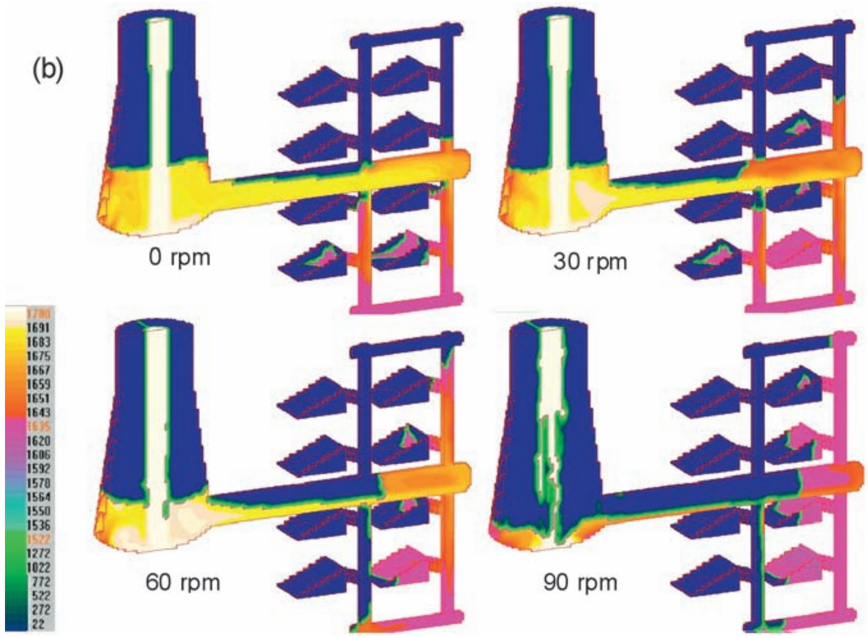

Fig. 5 Comparisons among the simulated centrifugal-mold-filling behavior (a centrally-longitudinal-section view) in the Fig. 2(b)-shown mold-cavity of different rotation-rates using a model without Coriolis-force consideration: at an initial mold-filling stage (a); at an early casting-cavity-filling stage (b)

90 rpm, the inlet alloy melt can be mostly thrown out when touching the bottom of the rotating sprue, rushing into the horizontal runner by the bottom surface, and tending to fill-up the farthest vertical gate first, then filling the casting-cavities backwards. Such casting-cavity-filling processes are principally driven by the corresponding paraboloidal pressure profiles in the alloy melt, built up by the centrifugal acceleration, $a_n = \omega_n^2 r_A$ [4]. This mold-filling behavior is similar to the previously simulated results [10, 24].

Figure 6 gives an outside view and a horizontal-section view through the axis of the horizontal runner for the same simulated mold-filling behavior as shown in Fig. 5(b) for the cases with mold-rotation rates of 30 rpm and 60 rpm. These figures may offer more information confirming that, under the assumed condition of no Coriolis force being present, the filling melt in the horizontal runner will touch the lower side of runner-cavity due to gravity.

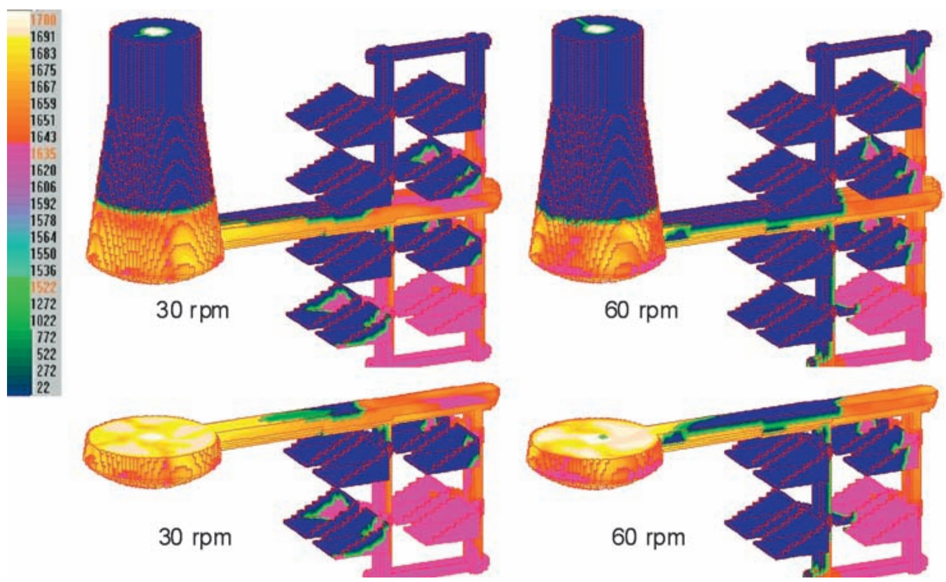

Fig. 6 An outside view (upper row) and a horizontal-section view (lower row) for the simulated centrifugal mold-filling behavior at the same mold-filling stage as shown by Fig. 5(b) for the cases with mold-rotation rates of 30 rpm and 60 rpm (without Coriolis-force consideration)

Quite different filling-behavior in this cavity-part will be seen below when using a full model with the Coriolis-effect. From the color-presentations for the melt-filled domains and the C-T scale shown in Figs. 5 and 6 it also can be seen that, due to the strong cooling from the mold, the excess temperature of the pouring alloy melt (~60 ℃) is lost quickly and solidification begins in the vertical gating frame and especially in the casting-parts because of the thin sections (~5 mm in the thicknesses of the dustpan-like castings). Similar solidification-heat-transfer phenomena will also be seen in the following computational cases of Figs. 7, 9 and 10.

Comparisons among the simulated mold-filling behavior at different positive mold-rotation rates from 0 to 250 rpm, but all with approximately the same filled melt-volume as that of Figs. 5(b) and 6, are shown in Fig. 7. These computational results are obtained using the full model of Eqs. (1) to (5), in which all the driving forces from the gravity, centrifugal and Coriolis accelerations have been taken into account. Again it can be seen that the mold-filling abilities of the alloy melt can be significantly enhanced in a centrifugal casting process.

Furthermore, by comparing each case shown in Fig. 7, it also can be seen that a higher mold-rotation rate tends to cause the filling melt free-surfaces, backwards to the rotating z-axis in the casting-part-cavities, to be more vertical. The envelope for these free surfaces can be closely described by a paraboloid predicted from the hydrostatics for a steadily rotating fluid system at the corresponding rotation rate, though the mold-filling is still in progress. This can be seen by referring to Fig. 8, which shows a group of analytical predictions[2, 4] for the free surfaces of a stably-rotating fluid system at rotation rates of 30, 60, 90, 120, 150, 180 and 250 rpm, respectively (where, $r=\sqrt{x^2+y^2}$). Such free surfaces, and the isopiestic paraboloids inside the rotating melt as well, are built up in fact by the centrifugal acceleration, $\omega_n^2 r_A$, which is dependent only on the angular-velocity and position. A conclusion can also be drawn from the simulated results comparison of Fig. 7, namely, that for the present "turn-back" centrifugal-casting configuration, a mold-rotation rate around 200 rpm might be high enough to achieve a rational technological control, i.e. in a smooth and layer-by-layer casting-cavities-filling manner.

Comparing the simulated results of Figs. 5 and 6 with that of Fig. 7 shows that the filling processes, i.e. VOF patterns, in the casting-part cavities are almost the same as each other for the corresponding mold-rotation rates, e.g. for the cases of ω_o = 30, 60 and 90 rpm, except for in the horizontal runners. Unlike the results predicted by the reduced model without the Coriolis-force, the filling melt keeps touching the right-side wall of the runner, viewed in the runner-filling direction, in the simulated results of Fig. 7 (with a counter-clockwise mold-rotating direction), in which the Coriolis term of Eq. (2), $-2\omega_o \times v$, has been taken into account. To further reveal the Coriolis-effects on the flow behavior in the horizontal runners, an additional group of computations with different clockwise mold-rotation rates corresponding to those in Fig. 7 were performed using the full mathematical model. The simulated results and comparisons with those at the corresponding counterclockwise mold-rotation rates are shown in Fig. 9 and Fig. 10, respectively.

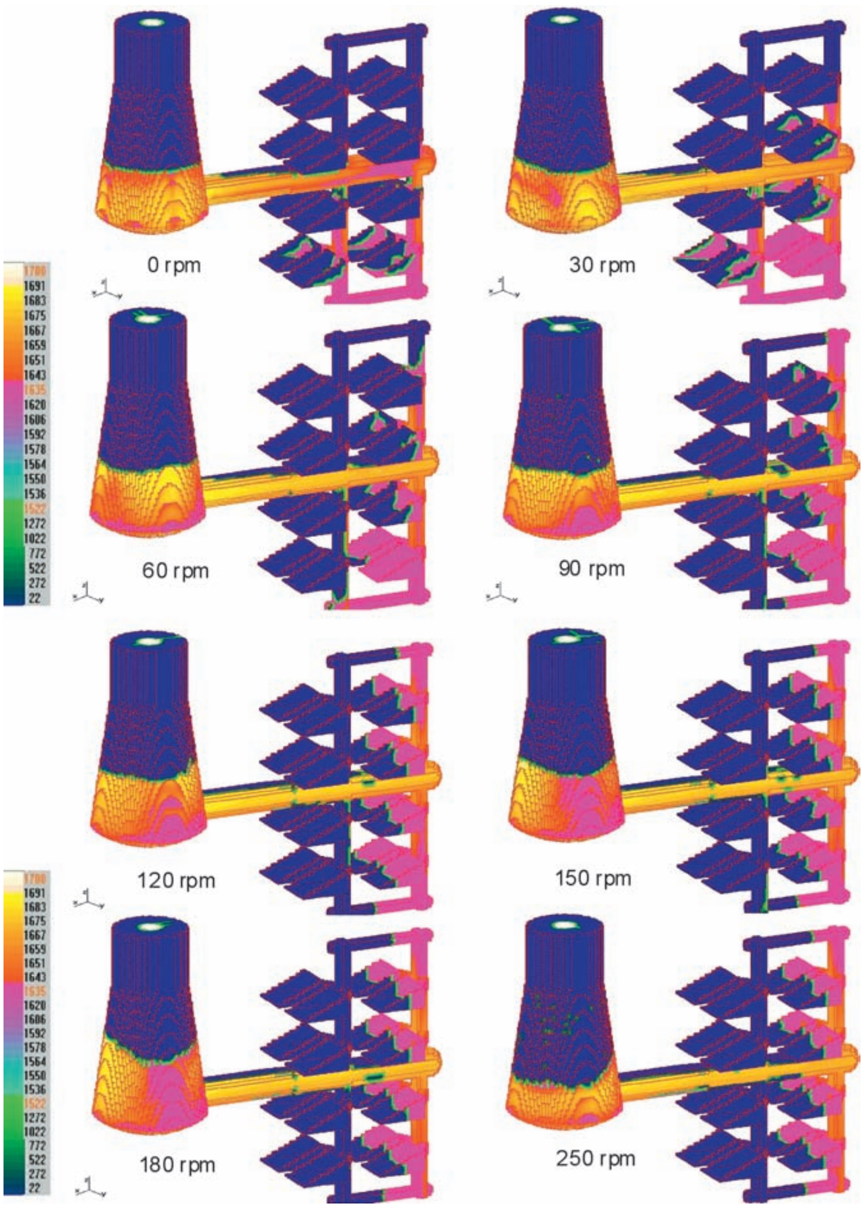

Fig. 7 Comparisons among the simulated centrifugal-mold-filling behaviors (an outside view) in the Fig. 2(b)-shown mold-cavity with different positive rotation rates from 0 to 250 rpm using the full model of Eqs. (1)–(5) (with the gravity and centrifugal + Coriolis forces).

From Fig. 9, it can be seen again that, except for the melt flow behavior in the horizontal runners, the filling VOF-patterns in casting-part cavities are almost the same as both those of Fig. 7 and Figs. 5 and 6 for the corresponding mold-rotation rates. However, due to the clockwise mold-turning direction for the mold-filling cases of Fig. 9, the flowing alloy melts in the horizontal runners keep touching the left-side walls, rather than the right-sides of the runners as shown in Fig. 7. Figure 10 gives a clearer comparison between the horizontal-runner flowing behavior, in a horizontally sectioned view through the runner axes, with different turning-directions for the different corresponding rotating-velocities. Furthermore, the Coriolis acceleration is dependent on both the directions and magnitudes of the rotation rate and the velocity. With the mold-rotation rate increasing, the alloy melts should be more likely to touch the side-walls of the horizontal-runners while filling the mold-cavity of the far end. This is also clearly confirmed by the comparisons of the calculated results made in Fig. 10 for the different mold-rotation rates.

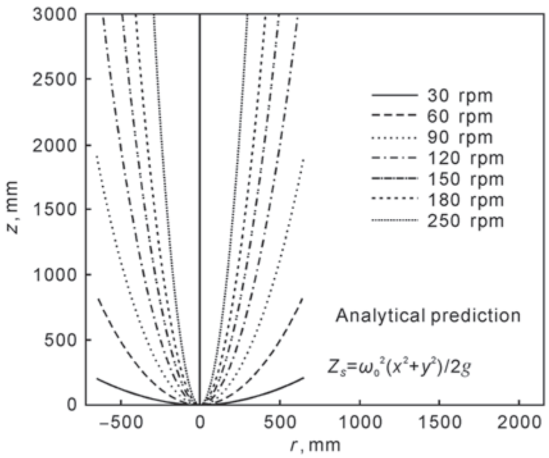

Fig. 8 Analytical predictions for the free surface curves of a fluid medium rotating steadily at different rotation-rates

4 Conclusions

The present computer codes, 3DLX-WSIM, employing the coupled mathematical model of Eqs. (1) to (5) and a SOLA-VOF algorithm under a rotating coordinate system, has been shown to be available for the numerical simulation of a centrifugal mold-filling and coupled heat-transfer processes. The computational results for the mold-filling behavior of Ti-6Al-4V melt in a vertical centrifugal-casting process with two horizontal plate-casting cavities show a reasonable agreement with the experimental observations performed in the literature [22].

The present numerical investigations also indicate that, due to the dependency of the Coriolis force on the direction and magnitudes of the rotation rate and the velocity, the mold-filling-pattern variations in the cavity-parts, that directly connect to the vertical sprue and have a large horizontal-section area, in a vertical centrifugal-casting system may be highly sensitive to the processing-parameters (e.g. ω_o, V_o, etc). To avoid the formation of possible related casting-defects, such as gas-holes/inclusions, entrapments, cold shuts, etc., a more complex gating system should be designed that can avoid the direct casting-cavity-filling occurring. A "turn-back" mold-filling technique, which only takes advantage of the centrifugal force in a transient rotating melt system, has been shown again to be a rational vertical centrifugal-casting process, in order to achieve a smooth and layer-by-layer casting-cavities-filling control.

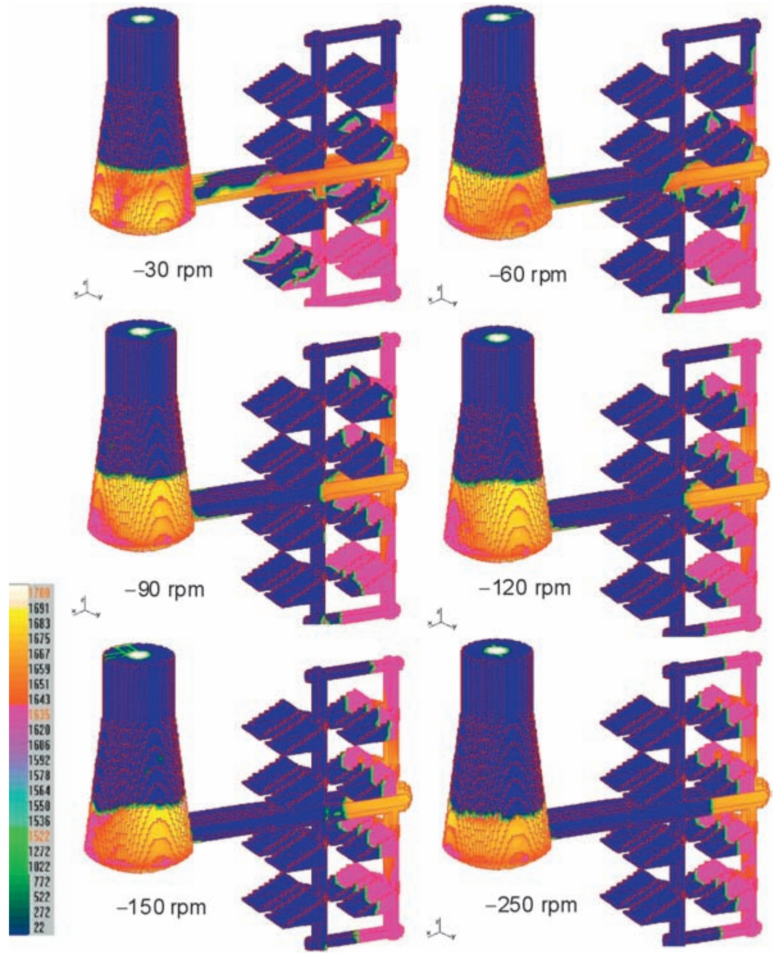

Fig. 9 Comparisons among the simulated centrifugal-mold-filling behaviours (a outside view) in the Fig. 2(b) mold-cavity with different clockwise rotation rates from -30 to -250 rpm using the full model of Eqs. (1) - (5) (with gravity and centrifugal +Coriolis forces).

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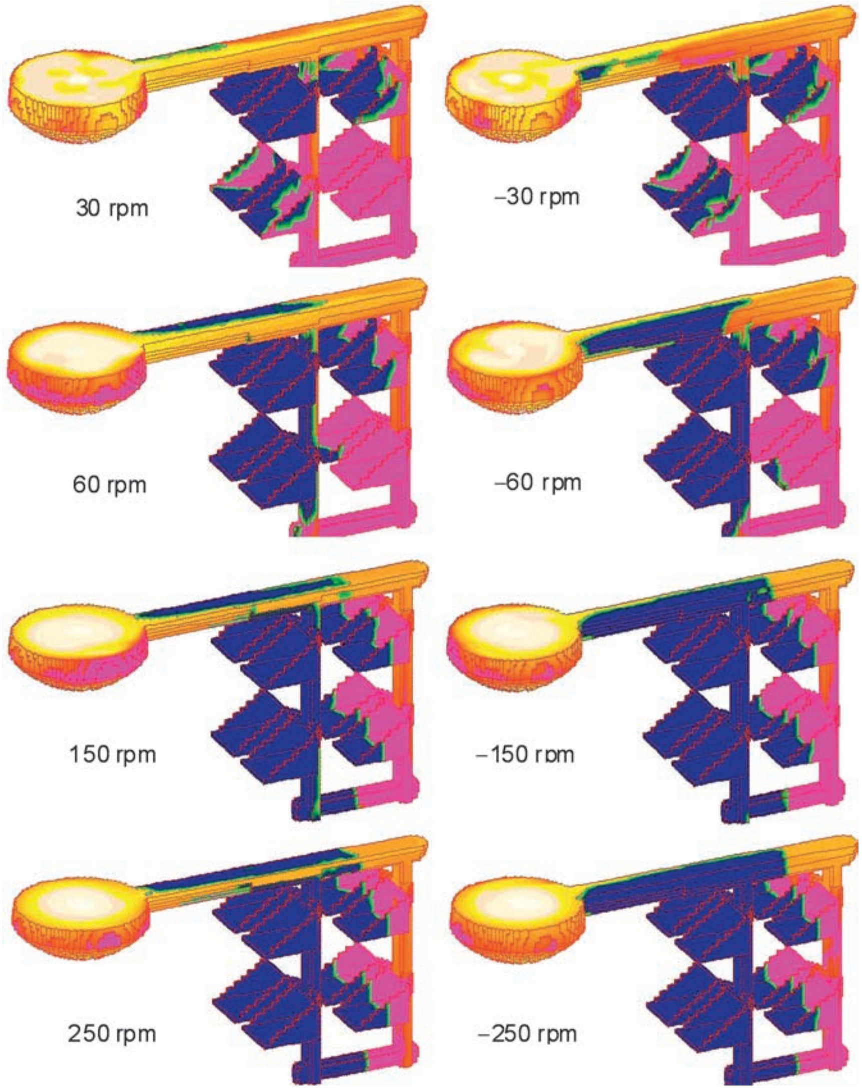

Fig. 10: Comparisons between the centrifugal-mold-filling behaviors (a horizontally-sectioned view) in the Fig. 2(b) mold-cavity rotating at different rotation rates and different turning-directions using the full computational model of Eqs. (1) – (5).

The study was supported by the NNSF of China (key program, grant No. 50291012) and a National Key Project.